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Preliminary assessment of the application of IKONOS satellite imagery and its fusion with RADARSAT-1 data for forest resource management

by

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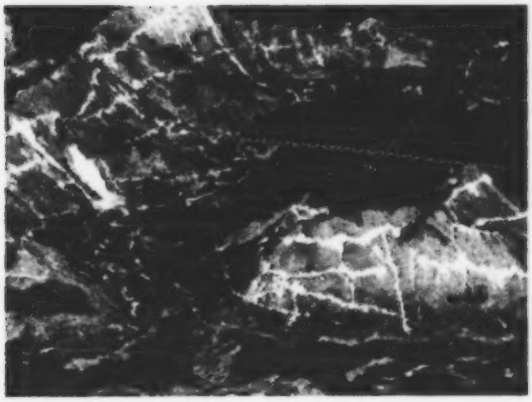

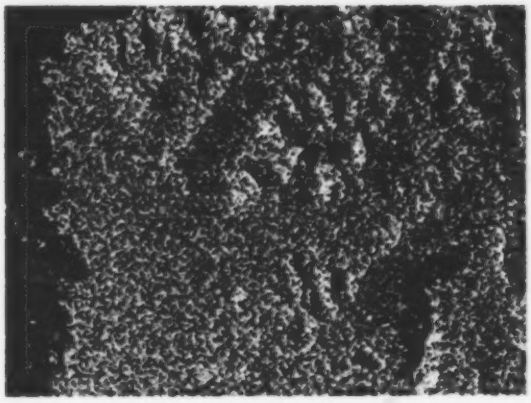

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Cover photo: Digital elevation model using IKONOS imagery and overview RADARSAT-1 image of study area.

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ABSTRACT

Remote sensing technology offers numerous options for the ability to view areas for the purposes of sustainable forest management. Aerial photography, either black-and-white or colour, and of variable scale, is one remote sensing technology that most forest resource managers are currently familiar with. More recently, satellite imagery has begun to offer remote sensing options that can be added to the toolbox of the forest resource manager. For example, active RADARSAT-1 imagery may be obtained regardless of cloud cover and solar illumination, which is an important feature during the winter months. However, the resolution is not optimal for forest resource management. On the other hand, passive IKONOS imagery relies on solar illumination and cloud-free coverage and has high spatial resolution.

The primary objective of this pilot project was to determine the suitability of using IKONOS high spatial resolution optical satellite imagery for forest resource management applications and monitoring in variable terrain. A secondary objective was to determine whether RADARSAT-1 imagery could be utilized in conjunction with the optical imagery to provide enhanced definition of regional scale geological features. Such a capability can be important for terrain mapping, and also to enable environmental monitoring during winter months when there could be increased sediment input into stream systems.

The imagery was analysed for the purpose of classifying resource features associated with forestry operations in an area adjacent to Clayoquot Sound on the west coast of Vancouver Island. These features include conventional clearcut harvesting, variable retention harvesting, roads, landslides, coarse woody debris, riparian areas, windthrow, and watershed restoration activities. Accuracy comparisons were made in relation to GPS ground control points. The relative costs and benefits of remote sensing and ground-based resource feature identification and mapping options were given a preliminary assessment, relative to the primary management objectives at hand. Recommendations for future related work are also presented in this report.

While RADARSAT-1 imagery has the advantage of being weather independent, its utility for routine forest resource management at an operational level requires expertise that is available only to a limited number of specialists. The use of stereo pairs could be of more use in operational forestry and terrain analysis applications than is shown in this pilot project.

This work demonstrates the capabilities of high spatial resolution IKONOS satellite imagery to discriminate and map forest resource features. The high spatial resolution IKONOS imagery is an important tool in the assessment, characterization and documentation of the main forest resource features in a watershed, and provides a new and valuable source of detailed information for environmental monitoring and development planning. Further work is required to demonstrate the application of this type of imagery to vegetation inventories. However, this type of imagery should form an integral part of the toolkit available to forest resource managers.

1.0 INTRODUCTION

The sustainable management of forest resources requires current and accurate information regarding the extent and nature of many resource features. Conventional information gathering relies heavily on ground-based methods of measuring and monitoring forestry operations. This is difficult in many remote or relatively inaccessible areas along the coast of BC.

The primary goal of this pilot project was to determine the feasibility and effectiveness of locating and mapping forest resource management features on the west coast of Vancouver Island using a recently launched high-resolution optical spaceborne sensor. A secondary objective was to determine the utility of merging this data with **RADAR**[1] data for environmental monitoring purposes during periods of cloudy weather.

The two types of images used were a) IKONOS satellite imagery and b) RADARSAT-1 imagery. The imagery from the IKONOS satellite was used to determine whether forest resource features could be accurately discerned. In addition, the IKONOS data was fused with the RADARSAT-1 data to determine whether the latter could be of benefit for environmental monitoring during cloud cover periods. The premise was that the optical data would provide detailed spectral information useful for discriminating between surface features, while the RADAR imagery would highlight the regional geologic structure and enable any new significant mass wasting events to be detected during periods of cloud cover. In addition, three different RADARSAT-1 images with varying beam mode incidence angles (positions) were acquired to determine which incidence angle provides the clearest delineation of resource features. Other ancillary data such as Global Positioning System (GPS) data was combined with the imagery to provide additional ground control data points for accuracy comparisons.

The resource features of interest from an operational forest management perspective include, but are not necessarily limited to, the following:

- Topography
- Landforms
- Landslides
- Roads
- Cutblocks, both clearcut and partial harvesting
- Vegetation types
- Stream channels and other aquatic and riparian features
- Wildlife habitats
- Coarse woody debris
- Windthrow

Regarding these resource features, remote sensing imagery has the potential to enable measurement and monitoring of changes, both temporal and spatial, in distribution, condition, and extent. Measurements may include linear distances and bearings (e.g., roads and cutblock boundaries), area determination, and derived volume calculations (e.g., for timber harvesting). Monitoring may include presence or absence of indicators (e.g., habitat condition), progress and results of resource management activities (e.g., road deactivation), and compliance with conditions of resource management planning (e.g., harvesting in accordance with an approved Silviculture Prescription).

[1] Words in bold are defined in the Glossary in Appendix A.

KEY WORDS

remote sensing, IKONOS, RADARSAT-1, forest resource management, variable retention mapping, forest inventory update.

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2.0 METHODOLOGY

2.1 STUDY AREA

This preliminary assessment of the IKONOS and RADARSAT-1 data was conducted on the Hesquiat/Escalante areas, located within and adjacent to Clayoquot Sound on the west coast of Vancouver Island (Figure 1). The area is within the South Island Forest District of the Vancouver Forest Region[2].

The area was chosen due to the significant amount of pre-existing digital and on-ground data available for this area as a legacy of the Forest Renewal BC programs in the area. The topography in the area ranges from flat to steep sided terrain, with elevations ranging from sea level along the coastal plain north of the Estevan Peninsula to approximately 1000 m elevation inland. The flats, known as the Estevan Coastal Plain, extend inland for approximately 6 km from the Escalante River mouth and encompass the Hesquiat peninsula. Much of the area was

[2] The Vancouver Forest Region is one of six administrative areas in the province of BC, as designated by the BC Ministry of Forests. It is located in the southwestern portion of the province, and comprises the South Coast, the Mid Coast, Queen Charlotte Islands, and Vancouver Island.

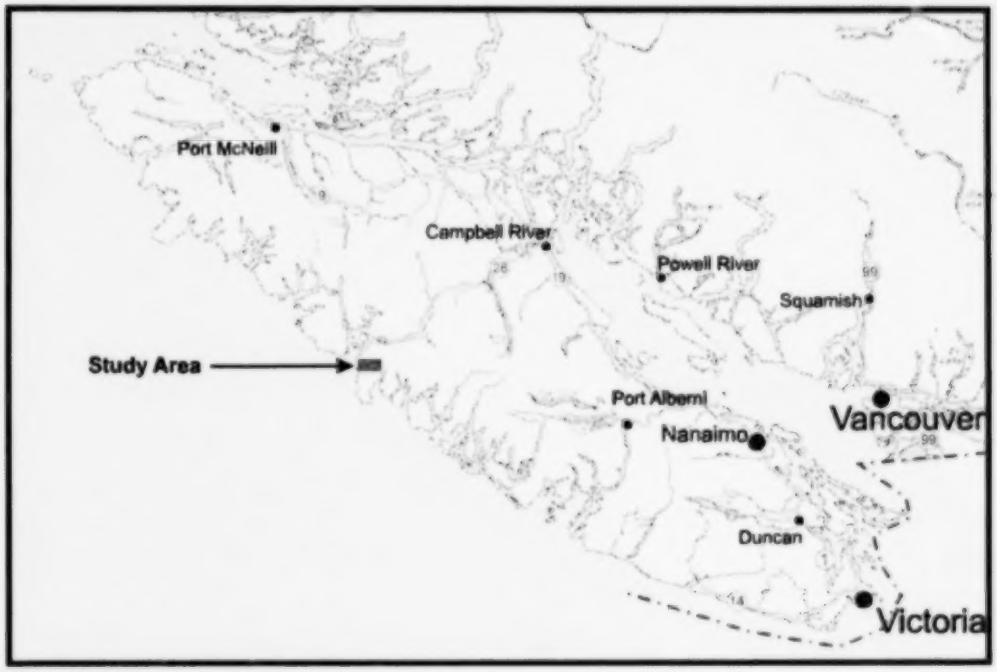

Figure 1. Study area location.

logged in the 1960s and into the 1980s but some recent variable retention logging is being conducted. There are numerous pre-Forest Practices Code (FPC) and some natural landslides in the area (Lewis and Liard,1983), many of which were initiated during an intense storm cycle in January 1996.

The area is predominantly underlain by granitoid rocks of the Island Intrusions and Westcoast Complex (Muller, 1977). Conglomerates and sandstone of the early Tertiary Escalante Group underlie part of the area, and similar lithologies of the Carmanah Group outcrop in the Hesquiat Lake area. In the North Fork of the Escalante watershed are outcrops of Karmutsen Volcanics, and the bedrock is metamorphosed and intensely sheared. This in conjunction with high rainfall and freeze-thaw processes produces a highly fractured and friable bedrock. This surficial material has resulted in the formation of deep colluvial blankets on many of the steep hillsides. Structurally controlled valleys have been glacially deepened and widened, a legacy of Quaternary glaciation. Preferential erosion along faults and other structural lineaments have eroded tributary valleys and deeply incised gully systems. Deep silty to gravelly tills, stratified gravelly glaciofluvial deposits, and laminated silts are present in the lower valley slopes.

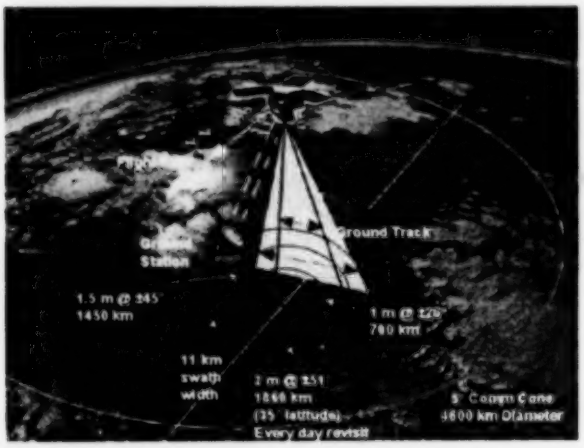

Figure 2. IKONOS satellite specifications.
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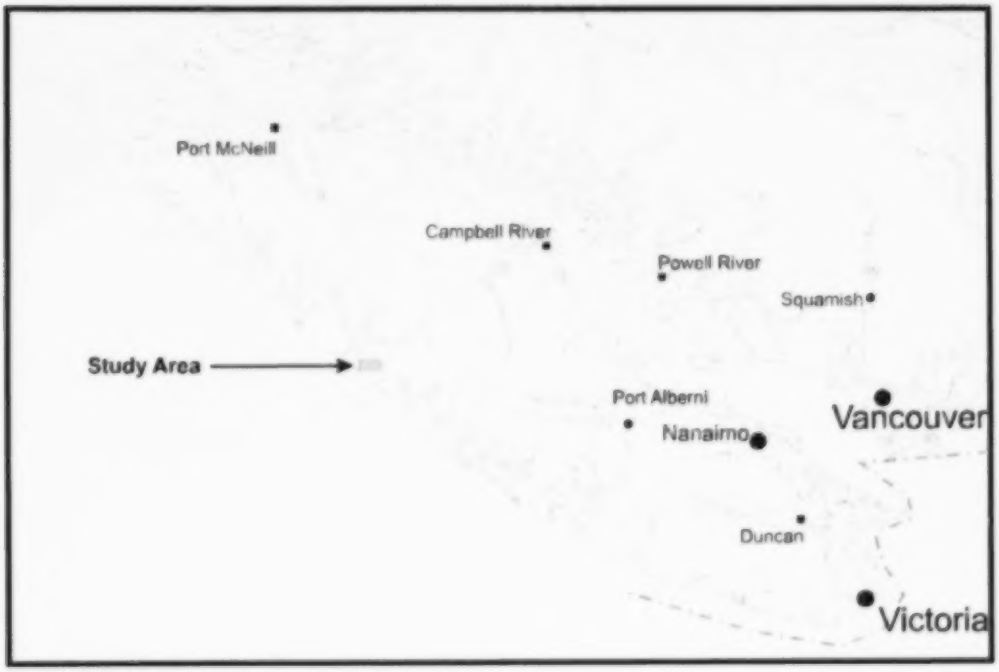
The weather of west coast Vancouver Island is dominated by Pacific cyclones that cause significant cloud cover and precipitation. The area is situated within the transition between the very humid and very wet maritime Coastal Western Hemlock biogeoclimatic zones (CWHvh and CWHvm). Predominant conifer species consist of western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*) and amabalis fir (*Abies amabilis*). Many of the older landslides are revegetated by red alder (*Alnus rubra*).

2.2 IKONOS SATELLITE

The IKONOS satellite was successfully launched on September 24, 1999. This is the first in a new generation of satellites collecting very high spatial resolution optical image data (Figure 2). The IKONOS satellite has a 1m resolution panchromatic sensor and a 4m resolution multispectral sensor (MSS). The multi-



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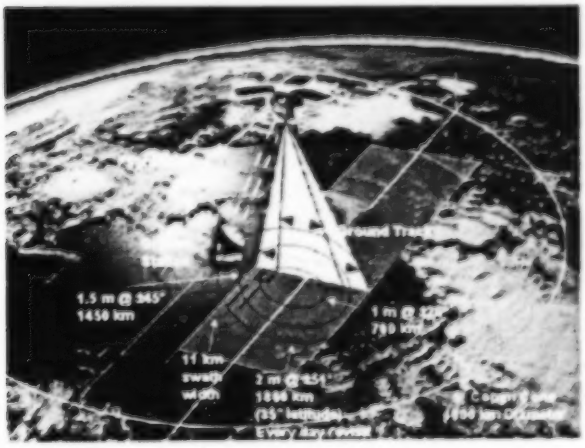

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spectral sensor provides the capability to view spectral information in the visible and near-infrared portions of the electromagnetic spectrum. The satellite orbits at an altitude of 680 km and has an orbit repeat cycle (temporal resolution) which ranges from one to three days. The technical specifications are outlined in Table 1.

Space Imaging, the operator of the satellite, supplies CARTERRA Geo products based on IKONOS imagery. Through a combination of different multispectral image channels, the IKONOS imagery provides a natural colour image, and a false colour infrared image that can be interpreted visually. The images are available as 1m resolution black-and-white and 4m resolution colour images. Both types of image are in 11-bit format, giving users 2,048 shades of grey or colour compared with the traditional 8-bit data, which provides only 256 shades of grey or colour. CARTERRA Geo products are sold by the square kilometer according to customer requirements. During this project, prices ranged from US $29/sq km to US $66/sq km for 1m black-and-white and 4m colour images, based on the level of geometric correction and the location of the world being mapped. The swath width for IKONOS images is 11 km (from http://www.spaceimaging.com).

2.3 RADARSAT-1 SATELLITE

RADAR instruments are used to transmit microwave signals and to receive the backscatter signal. They also measure the intensity and time delay of the return signals. The RADARSAT-1 satellite was launched on November 4, 1995, and is equipped with **Synthetic Aperture Radar** (SAR) which uses advanced signal processing techniques to simulate the effect of a long antenna. The satellite's orbit repeats every 24 days and the RADARSAT-1 fine beam mode image covers a **swath** area of 50 x 50 km. The RADARSAT-1 SAR has the following characteristics:

- C-band synthetic aperture RADAR (SAR).
- Cloud-free images.
- Seven beam modes offering a wide range of:
  - Resolutions (8 - 100 metres);
  - Swath widths (50 - 500 km);
  - Incidence angles (10 - 59 degrees).

A new satellite, RADARSAT-2, is being built by MacDonald Dettwiler of Richmond, BC, for a launch planned for 2003. Comprehensive reference material regarding RADARSAT-1 is available from the Radarsat International web site (http://www.rsi.ca/classroom).

A RADAR sensor does not look straight down, but rather down and to one side of the orbital plane. Known as oblique perspective, this is necessary so that the transmitted microwave pulse interacts with the terrain at increasing distances from the RADAR antenna, and thus provides the range dimension of the image. On an ascending pass from the South Pole the sensor looks to the east, and on a descending pass from the North Pole, it looks to the west.

One benefit of RADAR images is that the sensor receives in the microwave part of the electromagnetic spectrum, allowing it to work day or night. In addition, the sensor can penetrate clouds and rain, so the premise for this pilot project was that one can acquire an image as soon as possible for areas affected, for example, by a landslide. Some of the advantages of RADAR imagery are:

- **Active** remote sensing system generates its own scene illumination and records phase and polarization of reflected microwave energy;
- Not dependent on solar illumination;
- Penetrates clouds, rain, partially penetrates vegetation and soil;
- Produces different information than that available in the visible or infrared region of the spectrum.

However, RADAR is sensitive to:

- Surface roughness and aspect to the sensor which determines the **brightness** of the image;
- **Moisture**;
- Electrical properties;
- Motion.

Some disadvantages of RADAR are:

- Distortions inherent to RADAR imaging geometry;
- **Speckle**;
- Requires user familiarization and expertise for reliable interpretation.

The RADARSAT-1 Fine Beam mode is intended for applications which require the best spatial resolution available from the RADARSAT-1 system. The azimuth resolution is 8.4 m, with range resolution 9.1 m to 7.8 m from F1 to F5. Each Fine Beam position can be shifted either closer to or further away from nadir. The resulting positions are denoted by either an N (near) or F (far). For example, F1 is now complemented by F1N and F1F, which provides variations in the **slant range** and **incidence angles** across the swath.

Table 1. IKONOS specifications

Product Name	Spatial Resolution	Spectral Bands (Micrometers)	Dynamic Range
IKONOS 4 meter Multispectral	4 meter	Band 1: 0.45 - 0.53 (Blue) Band 2: 0.52 - 0.61 (Green) Band 3: 0.64 - 0.72 (Red) Band 4: 0.77 - 0.88 (Near Infrared)	11 Bit (2048 levels)
IKONOS 1 meter Panchromatic	1 meter	Pan Band: 0.45 - 0.90	11 Bit (2048 levels)

2.4 DATA ACQUISITION

The first part of the project was to map the area of Hesquiat and Escalante watersheds using the data from both the IKONOS and RADARSAT-1 satellites. The IKONOS imagery consisted of both panchromatic and multispectral imagery, and three different beam modes (F1, F2, F5) were acquired from the RADARSAT-1 sensor.

The coverage area for both satellites is shown in Figure 3. The area in red denotes the IKONOS coverage overlain on the RADARSAT-1 coverage.

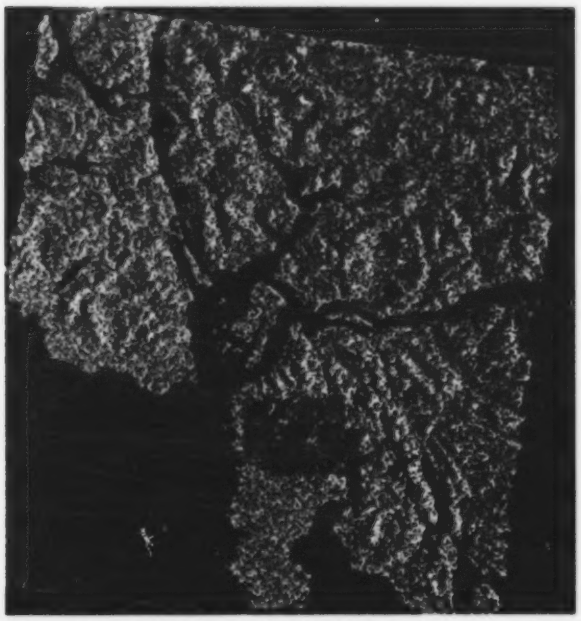


Figure 3. RADARSAT-1 and IKONOS (red) coverage areas.

2.4.1 RADARSAT-1 DATA ACQUISITION

The RADARSAT-1 images were acquired through the Satellite Acquisition Services (SAS) department of the Canadian Centre for Remote Sensing (CCRS) in Ottawa. Some difficulties occurred during acquisition of the imagery. Some of the missions were abandoned by the Canadian Space Agency (CSA) which operates the satellite and these then had to be replanned. Other images were acquired but were rejected by the CSA due to quality control parameters. For all images, the CSA was asked to try to minimize the **automated gain control** (AGC) effects (autocorrecting for water/land differences in backscatter) as much as technically possible during image processing. Swath planning was done with the help of SAS Quicklook images that were initially supplied through the CEONet web site (http://ceonet.ccrs.nrcan.gc.ca) for verification that the image footprint coincided with the actual area of interest on the ground. One image was acquired as a Ghost image (free "thumbnail" image) such that it could be reviewed to verify the ground conditions prior to the decision to purchase. A disadvantage of the Ghost image orders is that they are always a low priority and can easily be abandoned by the CSA if there is a conflict with a regular order.

The SAS desk also performed an archive search for all fine beams covering the area of interest since the start of the year 2000. This produced three potential images (Figure 4). Two of these were F5 beams and one was an F4 beam mode.

Three RADARSAT-1 fine beam images using different incidence angles taken one month apart were procured. An attempt was made to get the dates of the three RADARSAT-1 scenes as close together as possible in order to avoid differences caused by the change in season, e.g., no-snow vs snow. The original plan was also to acquire images with the same orbit. Due to technical difficulties at CSA, the third scene was not acquired as requested and a new request had to be input to their system. Due to time constraints, a Descending orbit image was accepted as there were no Ascending orbit images that could be acquired (Table 2).

Figure 4. Results of fine beam mode image database archive search.

A Look-Up Table (LUT), which is intended to improve the appearance of the image, can be applied to the imagery at the ground station. The options were Land, Sea and Mixed. The Land LUT was chosen to be applied to the imagery; however, it may have been more appropriate to apply a Mixed LUT due to the areas of high relief in the images.

2.4.2 IKONOS DATA ACQUISITION

To order the IKONOS imagery, an ArcView shape file and corner coordinates of the area of interest were provided to Space Imaging. The initial 30-day search schedule was to acquire an image during August 2000, but the acquisition schedule had to be replanned due to 60% cloud cover in the area of interest at that time. Each search schedule expired after 30 days if the scene could not be acquired and the order had to be reconfirmed.

The IKONOS imagery was ordered in July 2000, and the cloud-free image was acquired in September 2000 (Table 3).

A Quicklook image was provided to verify the coverage, and it appeared that the entire area of interest was imaged. However, when the final image was delivered a discrepancy in coverage was noted. Through discussions with Pacific Geomatics Ltd. and Space Imaging, it was determined that the discrepancy was due to the type of map projection provided to the supplier. The final image consisted of a northern image and a southern image, for both the multispectral and the panchromatic channels. Therefore, while the actual area of interest covers 55 km^2, Space Imaging provided additional imagery coverage for the purpose of this pilot project.

These two images were mosaicked together by McElhanney Consulting Services Ltd. before geocoding the images. To geocode the images, McElhanney used the PCI® software (http://www.pci.on.ca), as that vendor had recently introduced an IKONOS orthocorrection module. For evaluation purposes, this module along with traditional geocoding with a **Digital Elevation Model** (DEM) was applied to the imagery. There was no difference in the accuracy of the geocoding. It was expected that the IKONOS orthocorrection module would produce better results, but this was not the case. Difficulties with applying the orthocorrection module to mosaicked IKONOS images were the subject of discussions between McElhanney and PCI®.

2.5 DIGITAL IMAGE PROCESSING METHODOLOGY

2.5.1 IKONOS IMAGE PROCESSING

The first step in the image processing was to **orthorectify** the satellite images, followed by the production of composite images for interpretation. All images were orthorectified to UTM

Table 3. IKONOS order details.

Order ID	46096
Date of acquisition	Sept 21, 2000
UL coordinates	49.5431° /126.525°
Pixel spacing	1 m panchromatic / 4 m multispectral

Zone 10, NAD83 datum.

Orthorectification of the IKONOS imagery followed these steps:

1. The IKONOS panchromatic and multispectral images were ingested into PCI®;
2. The two halves of the panchromatic image were mosaicked together, as were the two halves of the multispectral images;
3. **Ground Control Points** (GCPs) were identified in the IKONOS image which matched known features in the vector linework. An attempt was made to evenly distribute the locations of the ground control points across the imagery, as much as possible, so that the entire image could be rectified. The same GCPs were applied to the panchromatic and multispectral images. Appendix C shows the distribution of the GCPs and the Root Mean Square (RMS) error for each GCP in the image;
4. The DEM and vector linework which coincided with the area of interest was imported into PCI®. The DEM and some of the vector linework were provided from Terrain Resource Inventory Mapping (TRIM) data. The remainder of the vector linework came from GPS survey data collected and provided by Interfor;
5. The image was then orthocorrected using the DEM. An output pixel size of 1m was produced for the panchromatic imagery, and 4m pixel size was produced for the multispectral imagery;
6. The images were then imported into ER Mapper® for producing composite images and for merging with the RADARSAT images;

One of the digital processing techniques used for this project was **Principal Component Analysis** (PCA), which is a form of data merging or data compression. The PCA reduces the dimensionality or number of bands that the interpreter has to analyse to produce results. PCA is a statistical technique for compressing the spectral variance in multiple image bands into a subset of principal component (PC) bands, where each of the PC bands are uncorrelated with each other. This means that each PC band provides unique information not contained in the

Table 2. RADARSAT-1 scene description. SGF/LUT = land.

Scene ID	C0017583	M0225704.	C0018648
Date of acquisition	Sept 19, 2000	Oct 3, 2000	Nov 6, 2000
Orbit:	Ascending	Ascending	Descending
Beam Mode:	Fine 5 near beam	Fine 1 far beam	Fine 2 far beam
Scene centre	49° 32'N/126° 35'W	49° 32'N/126° 34'W	49° 38'N/126° 30'W
Pixel spacing	6.250m	6.250m	6.250m

other PC bands. The first PC band (PC1) is the average of the input bands. The second PC band (PC2) contains the second highest amount of scene variance that is not taken into account by the first PC band. This process continues until the last PC band, which contains the least amount of unique scene variance information. The last PC band usually contains scene noise.

As a result of the concentration of scene variance in the first few PC bands, this reduces the number of image bands that need to be analysed to produce results. One of the drawbacks of this type of analysis is that it is very scene dependent. All multispectral channels plus the panchromatic channel were analyzed together for the PCA. The factor loadings were then reviewed and chosen based on having an inverse relationship between the visible and near infrared channels. The bands that have very large positive and very large negative values were also checked as these could be viewed as pseudo ratios.

2.5.2 RADARSAT-1 IMAGE PROCESSING

Image rectification of RADARSAT-1 images followed these steps:

1. The images were ingested into PCI®;
2. The DEM and vector linework which coincided with the area of interest was imported into PCI®. The DEM and some of the vector linework were provided via TRIM. The remainder of the vector linework came from GPS survey data collected and provided by Interfor;
3. An Antenna Path Correction (APC) was applied to the raw images. APC performs a radiometric balancing of RADAR data to compensate for non-uniform illumination in the range direction caused by the antenna pattern. Antenna pattern effects usually appear as a gradual increase then decrease in mean column grey levels as the RADAR backscatter is received by the sensor in the range direction (PCI® online help). Additive function, first order, was applied to the F1 and F2 images. As the southern part of the F5 image was very dark, the file was rotated 90 degrees, then the APC was applied in a multiplicative mode, second order, then re-rotated back –90 degrees. A number of runs were applied to the image in order to select the correct mode and order;
4. GCPs were identified in the RADARSAT image which matched known features in the vector linework (both from survey and from TRIM). An attempt was made to evenly distribute the locations of the ground control points across the imagery, as much as possible, so that the entire image could be rectified. Appendix B shows the distribution of the GCPs and the RMS error for each GCP in each image;
5. The images were then orthorectified using the SRORTHO module. A 7x7 Kuan filter was applied to the image to reduce speckling in the image during the SRORTHO process. The Kuan filter smoothes the speckle in the image data without removing edges or sharp features in the images. More information about the Kuan filter is available through the PCI® online help or user documentation. The output pixel size for all three RADARSAT-1 images was 12.5 x 12.5 m;
6. The orthorectified images were overlain with the vector linework in order to ensure the positional accuracy of images;
7. The images were then imported into ER Mapper® software for producing composite images and for merging with the IKONOS images.

2.6 IMAGE INTERPRETATION AND ASSESSMENT

2.6.1 INTRODUCTION

The following images were used for interpretative purposes:

1. Geocoded IKONOS pan and multispectral images in ER Mapper® and TIFF formats;
2. Geocoded RADARSAT-1 Fine beam mode images (three images) in ER Mapper® and TIFF formats;

In addition, ER Mapper® algorithms with the fusion and image enhancements for the following image combinations were examined:

3. IKONOS red, green and blue channels with best RADARSAT-1 image;
4. IKONOS near-infrared, red, green channels with best RADARSAT-1 image;
5. IKONOS panchromatic with best RADARSAT-1 image;
6. **Principal Component** composite using **Correlation Eigenvectors** (PC2, PC4, PC5 of IKONOS image).

2.6.2 MANUAL INTERPRETATION

Manual interpretation of the imagery involves a systematic visual examination of the imagery with the objectives of a) identification, b) interpretation, and c) determining the significance of the resource features. The main elements used in the visual interpretation of images are differences in:

- tone/colour – objects have different light reflectance properties and also backscatter properties;
- texture – this is a measure of the smoothness or coarseness displayed;
- pattern – there may be a spatial arrangement of features evident;
- shape – features may have different shapes;
- size – mainlines versus deactivated roads;
- association – relationships of objects such as landslides and connectivity to streams;
- shadow – may cause problems by obscuring ground, e.g., canopy may cast shadow on mainstem.

It must be noted that orthorectification of any imagery causes distortion, as the process either stretches or compresses portions of the image as dictated by topography and the orthorectification algorithms. To various degrees, the distortion affects all the above visual interpretation elements, and the user must learn to adapt and allow for this. Referral to the raw image can assist with resource feature identification, although positional accuracy will be lost.

Because the scenes are acquired in a digital format, they can be

manipulated using digital processing software in a variety of ways to extract information pertinent to the user. There is still a need to use manual interpretation techniques, but the digital processing enables the process to be repeatable. Image enhancements can be used to improve the visual appearance of the image for interpretive requirements or for highlighting the features most important for the task at hand. The actual enhancement selection is dependant on the nature of the data and the elements in the scene. It should be noted, however, that stretching changes the value of the original pixels and is therefore not advisable, for example, in computer assisted classifications or change detections. One useful technique in resource infrastructure management is edge enhancement, which delineates edges or sharp changes in the brightness values between two contiguous pixels, thereby making sharp details easier to see and analyse.

2.6.3 ACCURACY

The use of the same DEM for rectification of the imagery made it possible to compare the positional accuracy of the imagery with the GPS survey points. The orthocorrected IKONOS image was overlain with GPS survey points to determine relative accuracy. The GPS data used as a baseline for the assessment was collected using a local corrected base station and is considered to be of sub-metre accuracy. Analysis of the orthocorrected IKONOS imagery with the GPS survey points demonstrates that the image generally has high spatial accuracy. An accuracy table (Table 4) shows the deviation in meters in the x and y dimension between a selection of GPS survey points and these locations in the IKONOS image. From the table, the y dimension error distance is almost always larger than the x dimension error distance. It is not known whether this discrepancy in error between the x and y dimensions is caused by the orthorectification algorithm, the DEM, our control point marking and distribution, or some other factor(s).

However, there are some places where the fit is not as good. An example is on the right side of the image where there is a cutblock trending east-west and above it, two cutblocks trending north-south. From measurements on the image, the east-west trending cutblock varies between 30 to 50m in positional accuracy. The positional inaccuracies for the cutblocks occur along the edges of the image. In addition, there is some smearing of the image between the two north-south cutblocks. This smearing is caused by the orthorectification software. It may be speculated that the positional inaccuracy and the smearing is caused by a combination of the location of the GCPs and the elevations in the DEM used for the orthorectification. In general, the edges of a satellite image tend to be not as accurately orthorectified as the middle of the satellite image, due to the mathematics of the rectification algorithm. Areas surrounded by GCPs can have their position accurately mapped, while areas that are not surrounded by GCPs only get an approximation of their position.

Absolute positional accuracy across the RADARSAT-1 images is difficult to ascertain, as many surveyed features are not visible in the RADARSAT images. The closest estimate for positional accuracy comes from a review of the RMS error report derived from the orthocorrection (this estimate describes the fit of the orthorectified data to the ortho model being used by PCI®). From these reports the positional accuracy was the best for the F1 image at 1.71 **pixels** in the x direction and 1.16 pixels in the y direction. The F2 and F5 images had lower positional accuracies in the 2 pixel range. This could be due in part to the fact that the sensor is pointing further from nadir for the F2 and F5 images, so the effects of foreshortening and layover are greater than for the more vertical F1 image.

2.6.4 DIGITAL IMAGE INTERPRETATION

2.6.4.1 RADARSAT-1 IMAGES

An overview of the use of RADAR digital imagery for mapping clearcuts has been documented by Leblon (1999). In addition, several studies have demonstrated that SAR imagery is a useful tool for geological mapping (Saint-Jean et al., 2000). After orthocorrecting the RADARSAT-1 images and importing them into ER Mapper®, the three orthorectified images were individually viewed and assessed for the suitability to detect features of interest in the image. A comparison of the three RADARSAT-1 beam modes is shown in Figure 5.

The descending F2 scene is visually different from the F1 and F5 ascending scenes and appears much smoother than the other images. In addition, the descending scene is significantly brighter

Table 4: Accuracy deviations

Survey Point ID	Distance (m)	Distance X (m)	Distance Y (m)	Surveyed Feature
95	2.91	1.9	2.2	Spur - Semi
363	15.02	9.3	11.8	Spur - Full
402	8.57	1.7	8.4	Mainline
276	5.3	2.8	4.5	Mainline
109	2.96	2.9	0.6	Mainline / Spur - Semi Intersection
207	1.36	1.1	0.8	Mainline / Stream Intersection
222	14.45	5.4	13.4	Mainline
599	18.76	5.6	17.9	Spur - Semi
521	16.48	11.5	11.8	Spur Semi / Spur Full Intersection
394	21.68	2.8	21.5	Mainline / Spur Semi Intersection

and more uniform across the entire image. The ascending scenes appear to show more changes in brightness and tone. One of the issues concerning acquisition of RADAR images is if the weather conditions are dry or rainy. If there was rain shortly before a RADAR image of an area was acquired, e.g. everything is still wet, the image will tend to be darker and more homogenous in tone. This may be the case with the descending F2 scene, since it was acquired in November 2000. The F2 scene may appear brighter, but this is just the effect of contrast stretching the image. However, the overall tone of the F2 image is smooth.

Two areas of interest are a variable retention (VR) block on the Escalante flats and an area of large landslides in the north fork of the Escalante River. Additional analysis was done on the VR block and the main landslide area to determine whether these features could be defined in the imagery. The digitized outline of the VR block and the landslides was incorporated for reference purposes (Figure 6).

The F5 image appears to show slightly more detail than the F1 and F2 images. This may be a result of the F5 incidence angle being more perpendicular to the slopes of the mountains in the image. Research by CCRS has indicated that geological detail is enhanced the more perpendicular the incidence angle is in relation to the terrain surface (Singhroy and Saint-Jean 1999). Singhroy and Mattar (2000) found that high resolution fine mode RADARSAT-1 imagery, although not as useful as the airborne InSAR images, can be used to identify some landslide features.

From the individual images, it was not possible to visually delineate the large landslide areas in this pilot project. There has been significant pre-FPC logging in the area, so the terrain surface would be very similar (e.g., early seral stage regeneration, shrubs, grasses), therefore it is likely that a very similar amount of reflection would be provided by the RADAR data to the sensor. It is possible that the slides may be detectable under circumstances where they are bounded by large trees, since one could expect that varying seral stage would present backscatter values that are distinctive and associated with the physical and scattering characteristics

The VR block could not be identified in all the RADARSAT images. This is surprising since the boundary between the roads and the trees forms corner reflectors which should provide a strong reflection back to the sensor. From a regional geologic perspective, the F5 image did appear to show two parallel NW - SE trending lineaments. The southern lineament, as it follows a river, was visible in all three RADARSAT images. The northern lineament was only identifiable in the F5 image.

The three orthorectified RADARSAT images were combined into an RGB colour composite (F1 being displayed in Red, F2 in Green and F5 in Blue) to determine if a colour composite could better define the landslides, VR block, other cutblocks, and geological features in the area (Figure 7). Together, the RADARSAT images did not provide any additional details to allow easy mapping of these features. Again, this would be a result of the fact that these features were not visible in the individual images. In the landslide area, roads were not visible, nor were the landslides. There is a colour shift in this RGB composite, as the slope with the landslide is coloured green (Figure 7). This is because F2 is displayed as green, and the F2 image was descending while the F1 and F5 are ascending. The F2 image appears as a mirror image in brightness compared with the F1 and F5 images. In the F2 image, the slope is facing the sensor and appears in bright tones. In the F1 and F5 images, the slope is facing away from the sensor and appears in dark tones.

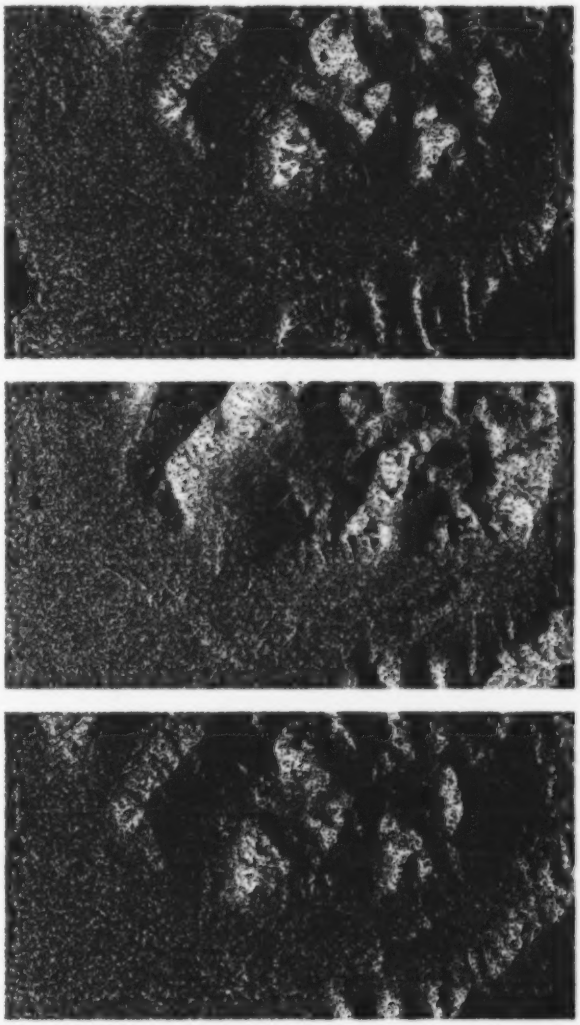


Figure 5. Comparison of RADARSAT-1 orthorectified images.
Top photo: F1 ascending orbit at incidence angle of 37.990. Note the shadow on the east side of the ridge in the northwest quadrant due to eastward satellite look direction.
Middle photo: F2 descending orbit at incidence angle of 40.710. Note the shadow on the west side of the ridge in the northwest quadrant due to westward satellite look direction.
Bottom photo: F5 ascending orbit at incidence angle of 46.180.

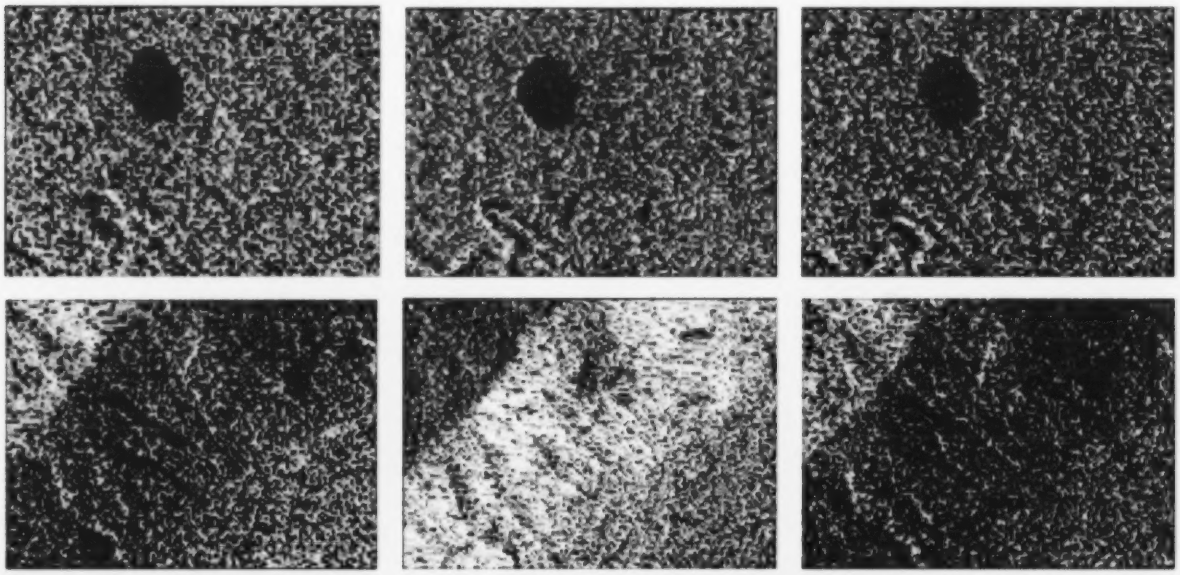


Figure 6. Digitized overlay of VR block and landslides on RADARSAT-1 images. Top row, left to right: VR block F1 RADARSAT, VR block F2 RADARSAT, VR block F5 RADARSAT. Bottom row, left to right: Landslides F1 RADARSAT, Landslides F2 RADARSAT, Landslides F5 RADARSAT.

2.6.4.2 IKONOS IMAGES

The PCA of the IKONOS images was produced with PC2 displayed as red, PC4 displayed as green, and PC5 displayed as blue. PC2 was selected as it shows an inverse relationship between the visible light channels (RGB) and the near-infrared (NIR) plus panchromatic channels. PC4 showed an inverse relationship between the blue and red light channels. The PCA colour composite shows differences between bare rock/soil areas in the image. For example, as will be discussed in Section 3.0, in the landslide area the landslides are shown in red and blue colours, while the roads in the area appear as a purple colour. In the near-infrared colour composite, the landslides and roads are both in bluish hues.

In the VR block, the particular combination of PC images did not provide any additional visual details compared with the NIR image for the area. It is possible, though, that changing the combination of PC images for the colour composite could show additional differentiation. Changing the PC colour combination may also be used to try to enhance differences in forest cover type and/or forest vigour.

Appendix D provides the scene statistics for the IKONOS imagery along with the correlation matrix, correlation eigenvector matrix, and the factor loadings for the PCs.

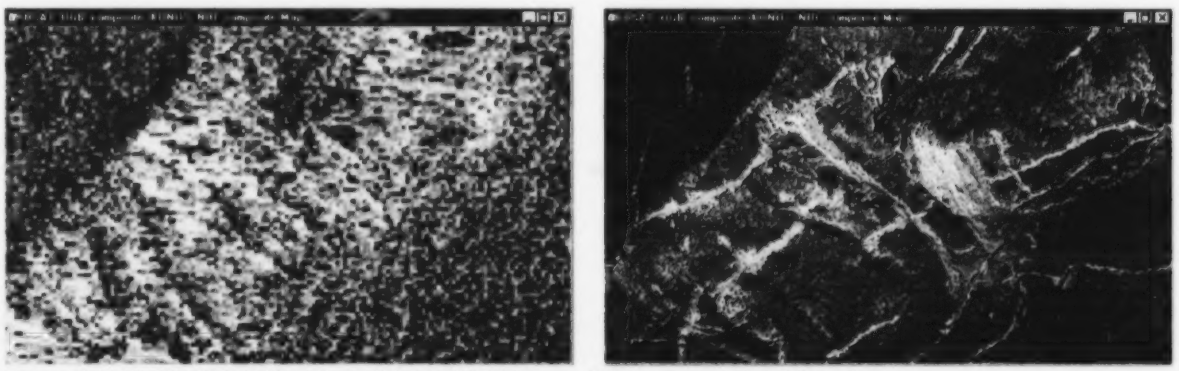


Figure 7. RADARSAT-1 RGB with the IKONOS NIR image of the same area (right) for reference.

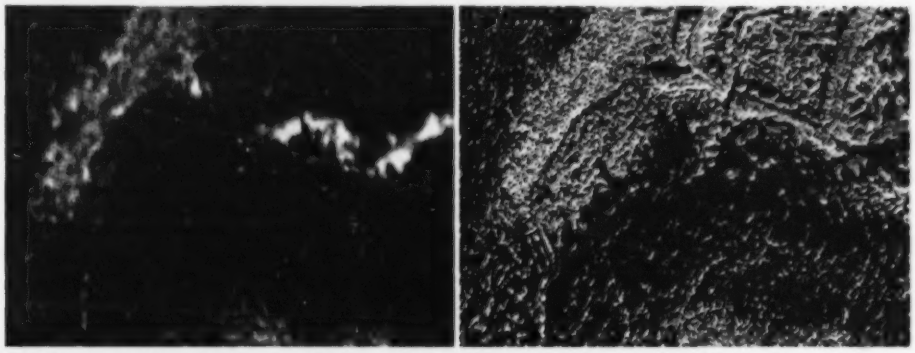


Figure 8. IKONOS natural colour image alone (left) and with panchromatic image merged.

2.6.4.3 NATURAL COLOUR AND NEAR-INFRARED COMPOSITES

The natural colour images (4m pixel) without the merged panchromatic image (1m pixel) are visually more blurry than the same images with the panchromatic image (Figure 8). The natural colour and near-infrared colour composites provided very useful images when fused with the panchromatic image to enhance spatial detail. Individual tree crowns, decked logs, coarse woody debris, landslides, roads, and many other features could be easily seen and digitized in these colour composites. The shape of the shadows cast by the trees could be clearly seen, which may, in the absence of stereo imagery, help identification of tree type in an area.

Since the images are in digital format, the use of edge enhancement filters and various contrast stretching techniques can enhance the image so that small details are easier to differentiate and map compared with a hardcopy photographic print.

2.6.4.4 IKONOS AND RADARSAT-1 IMAGERY FUSION

A secondary objective of this pilot project was to determine whether RADARSAT-1 imagery could be utilized in conjunction with optical IKONOS imagery to provide enhanced definition of regional scale geological features, which could be important from a terrain mapping perspective, and also to enable environmental monitoring during winter months. The premise is that if landslides could be differentiated on the RADARSAT-1 imagery, then this could be utilized for monitoring purposes following storm periods along the west coast. The IKONOS imagery would form the base map for the imagery.

Previous forestry studies using RADARSAT-1 imagery have largely concentrated on mapping clearcuts and riparian leave strips. Many studies have demonstrated that environmental conditions have a significant influence on the SAR backscatter from vegetation, and thereby alter the contrast between seral stages in individual images (e.g., Yatabe & Leckie, 1995). In addition, clearcut mapping is more accurate using multi-date images acquired during contrasting seasons (Leblon, 1999).

Figure 9 shows overview images of the north fork of the Escalante watershed: a) an IKONOS image, b) a RADARSAT-1 image, and c) a RADARSAT RGB composite.

The F5 image was selected as providing the best discrimination of features of interest. The F5 image was combined with the IKONOS imagery to see whether the RADARSAT image could help enhance structural features in the IKONOS imagery. As will be discussed in Section 3.0, the near-infrared colour composite provided additional information that was not visible in the natural colour composite. The addition of the RADARSAT-1 F5 image did not appear to enhance details in the IKONOS red, green and blue (RGB) channels image. The roads in the VR block appear as brown coloured features. The standing trees within the VR block are still green in appearance, but the boundaries of these trees are rendered diffuse. The addition of the RADARSAT image does appear to enhance the differences between forest cover types around the VR block. The trees to the south of the VR block are brighter and have a more distinct boundary in the combined image compared with the IKONOS image. Therefore, for road details it appears that IKONOS is better, but for mapping the boundary between different forest cover types the combination of IKONOS and RADARSAT may provide some benefit.

The next images show the NIR colour composite merged with RADARSAT imagery (Figure 10a) and the IKONOS NIR colour composite image of the same areas (Figure 10b).

In the north fork of the Escalante River area, a major fault plane outcrops and forms the headscarp of a large natural wedge failure rockslide (the landslide to the east in Figure 10). It has been demonstrated that RADARSAT-1 imagery enhances geologic features (Singhroy and Saint-Jean, 1997) and it was speculated that it would also enhance the traceability of this structure. Unfortunately the fault trace could not be delineated along geologic strike. Within the landslide area, the details from the IKONOS image were lost when combined with the RADARSAT image. Standing trees along the headscarp of the eastern landslide are easy to differentiate in the IKONOS image, but are diffuse in the merged image.

2.6.4.5 IKONOS PANCHROMATIC AND RADARSAT-1 IMAGERY FUSION

Two methods of merging the IKONOS panchromatic image with the RADARSAT-1 F5 image were tested. The first method

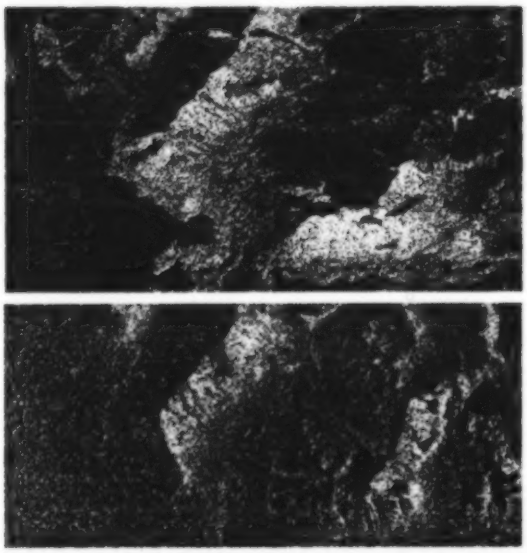


Figure 9. a) IKONOS (top left), b) RADARSAT-1 (top right), c) RADARSAT-1 RGB composite images.

was to multiply the IKONOS panchromatic image with the RADARSAT-1 F5 image. The second method was to display the IKONOS panchromatic image as an RGB image, then, using an intensity transform (RGBI), integrate the RADARSAT F5 image as an intensity channel. Other approaches were also tested where the RADARSAT was used as the RGB image and IKONOS as the intensity image, but the resultant image looked

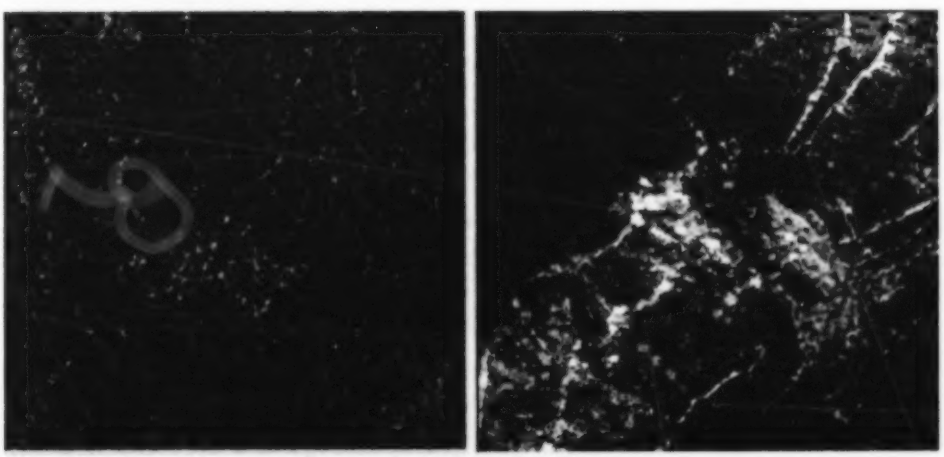


Figure 10a. NIR colour composite merged with RADARSAT imagery

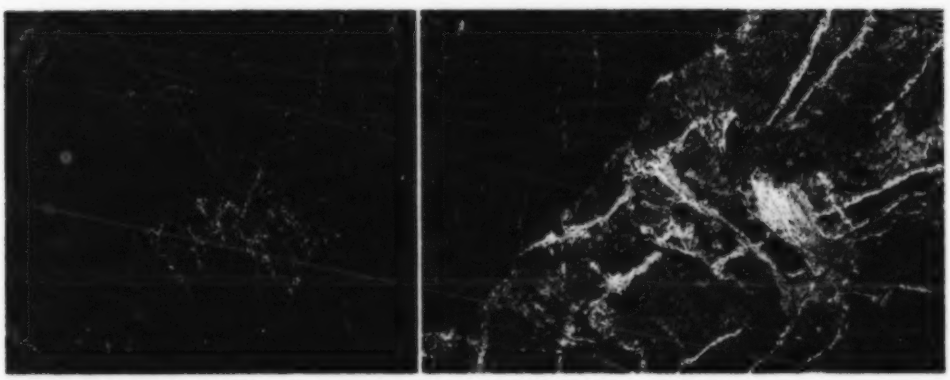


Figure 10b. IKONOS NIR colour composite image of VR block and landslides.

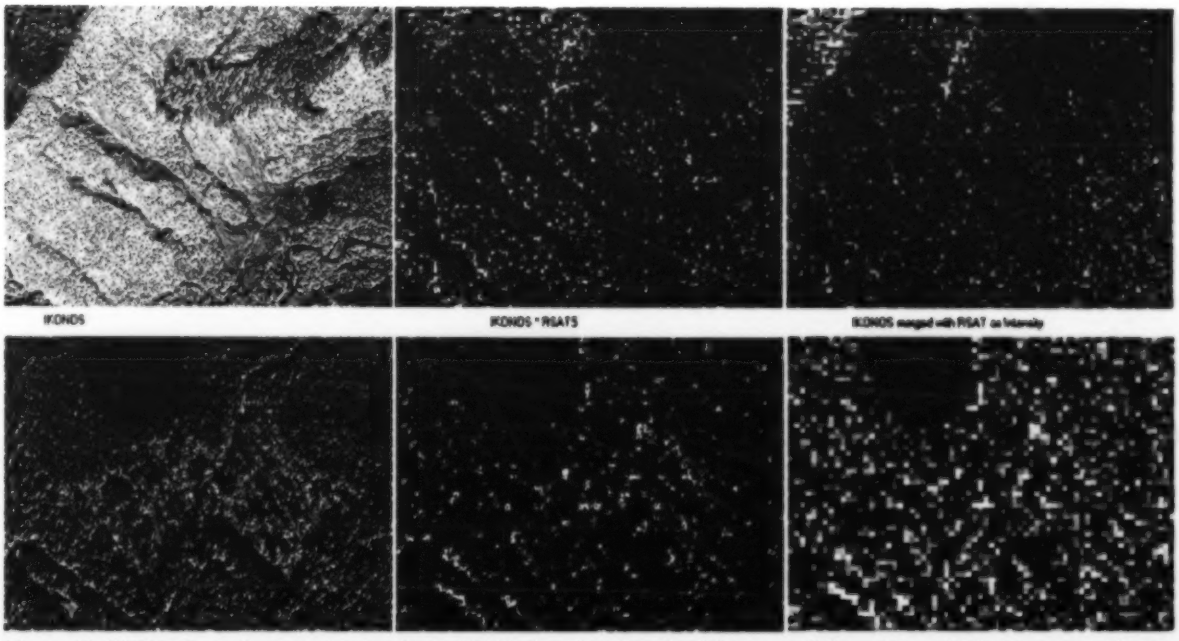


Figure 11. IKONOS panchromatic images for the VR block and the large landslide areas, followed by multiplied images and finally by the RGBI image.

just like the IKONOS image, and the RADARSAT image could not be distinguished. Square rooting the two images and then summing them together also did not result in a useful image.

Figure 11 shows the IKONOS panchromatic images for the VR block and the large landslide areas, followed by the multiplied images and finally by the RGBI image.

The RGBI image tends to show less spatial detail than the multiply image. In the VR block, some of the spatial detail can be recognized in the multiply image when compared with the IKONOS image for reference. However, the addition of the RADARSAT data does not appear to highlight any features that are not easily recognized in the IKONOS image. The forested area to the north of the VR block has more variation in the multiply merge compared with the IKONOS image. All the variability from very dark to very bright is a direct result of the RADARSAT image. Edges in this part of the image – as identified by the road leading to the VR block and the stream to the south of the VR block – are still recognizable in the multiply image. Smaller edges, such as those within the VR block, are not easily identifiable. The RADARSAT image overpowers the IKONOS image in the RGBI merge. No more features are recognizable than are in the RADARSAT image alone.

In the landslide area, the multiply image again shows more detail than the RGBI image. The RGBI image has a smoother overall tone compared with the multiply image. The landslides are displayed as dark linear features within both images. Without knowing that this is a landslide area, one could easily misinterpret these dark features as steep sided gullies. The large block of standing timber to the northeast of the natural landslide is shown as a dark speckled area. Again, this area could not be easily identified as forest without prior knowledge of the area or having other images of the area.

Therefore, it is possible to differentiate large landslides using the multiply image fusion of IKONOS and RADARSAT-1 F5 imagery, but it is likely that smaller events would be difficult to delineate. In an emergency situation there may be some benefit to acquiring RADARSAT-1 imagery following storm periods, but it is not recommended to merge together RADARSAT F5 imagery with IKONOS panchromatic imagery on a routine operational basis.

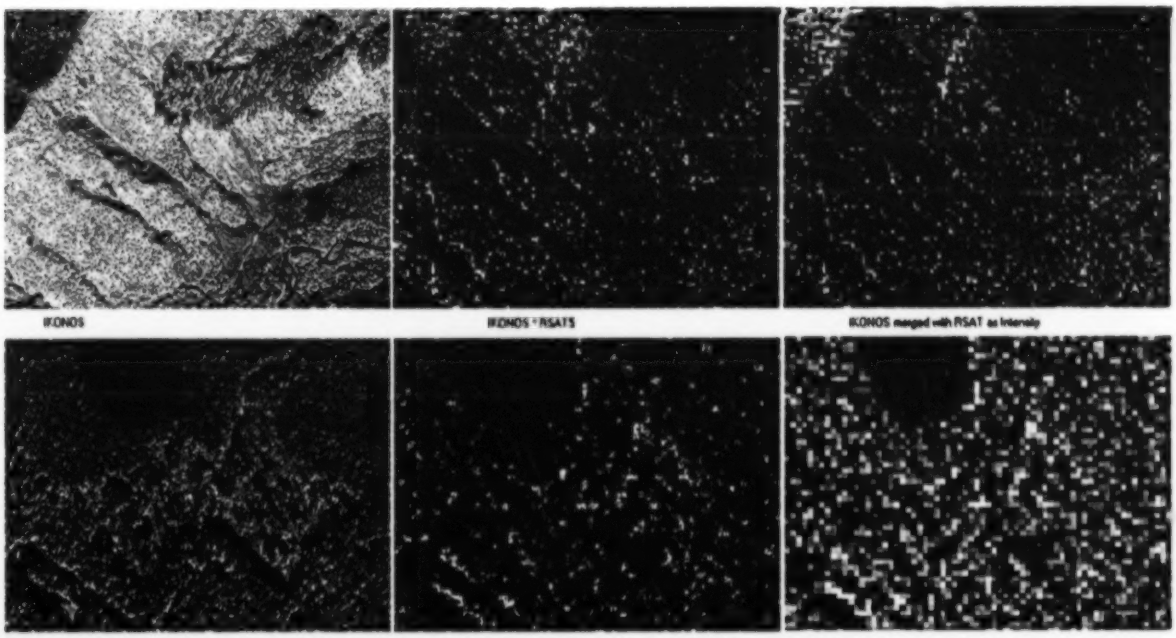
3.0 FOREST RESOURCE MANAGEMENT APPLICATIONS

3.1 IKONOS APPLICATIONS

A comparison of the high spatial resolution optical data and RADAR data for this pilot project demonstrated that the IKONOS was most user-friendly for operational forestry applications. Therefore, the focus of this section is on the potential forestry applications of the IKONOS imagery.

3.1.1 LANDSLIDES

Mapping of terrain stability and landslide hazards is a requirement for many forest development plans in BC, especially on the coast and in community watersheds. Landslides and other major sediment sources may be classified from the IKONOS imagery. The types of disturbance, origins or initiation points, area of disturbance and runout zones, connectivity to streams, and degree of revegetation are all identifiable. The landslides



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Mapping of terrain stability and landslide hazards is a requirement for many forest development plans in BC, especially on the coast and in community watersheds. Landslides and other major sediment sources may be classified from the IKONOS imagery. The types of disturbance, origins or initiation points, area of disturbance and runout zones, connectivity to streams, and degree of revegetation are all identifiable. The landslides

can be classified by their points of initiation. In addition, the spatial distribution of the sediment sources is readily apparent. As with air photo interpretation, any landslide less than 0.05 ha is likely too small to be seen under a tree canopy.

Figure 12a shows a road fill failure and a natural rock fall wedge failure. The extent of both of these events is easily delineated on the IKONOS image, and the area of the landslides can be calculated by digitizing the boundaries. The NIR imagery is useful for differentiating the area occupied by slide material rather than vegetation. The landslide on the left of Figure 12a was revegetated with grass seed and alder in an attempt to mitigate sediment mobilization, but reactivation of the headscarp and sidewalls subsequently occurred. The areas of revegetation are evident within the slide track transport zone. In addition the trace of a deflection berm on the desposition zone which was constructed to contain some of the slide material is evident even though it was breached and overwhelmed in subsequent events.

Landslides with different points of initiation are identifiable on the IKONOS imagery. As shown in Figure 12b and 12c, the NIR images can be useful for the determination of road fill and open slope failures.

Landslide areas can also be calculated from the IKONOS imagery. Varying types of landslides (Figure 13) were randomly chosen and digitized to calculate their areas. The resulting areas correspond closely to the areas that have been estimated during onground reviews of these landslides, and in fact may be more accurate. The calculated areas are provided in Table 5.

3.1.2 INCIPIENT SLIDE AND EROSION ZONE IDENTIFICATION USING PCA AND NIR IMAGERY

The PCA of the IKONOS images was produced with PC2 displayed as red, PC4 displayed as green and PC5 displayed as blue. The PCA colour composite showed differences between bare rock/soil areas in the image. However, because of image uniqueness, one cannot use this as a typical characterization of each type of thematic class under consideration. For example, around the landslide area (Figure 14), the landslides and roads are shown in strong red and purple colours, while the surrounding conifer vegetation is shown in a light colour. While much of the deactivated road is grass covered, such areas do not have a conifer cover. Areas in red signify denuded, but not actively raveling,

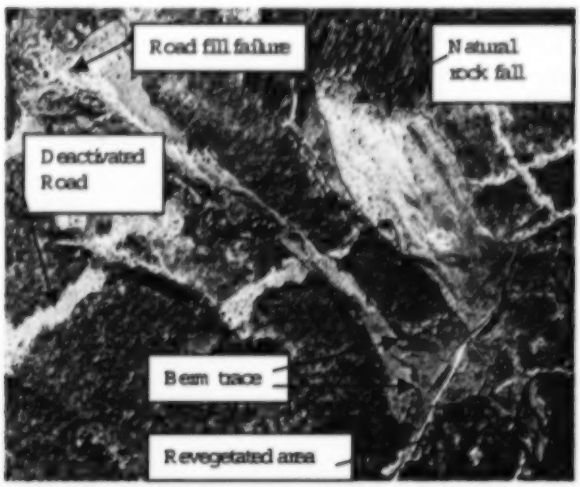

Figure 12a. Road fill failure and rock fall from IKONOS image.

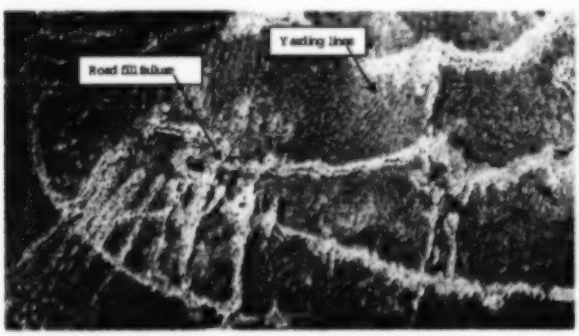

Figure 12b. Road fill failure from IKONOS image.

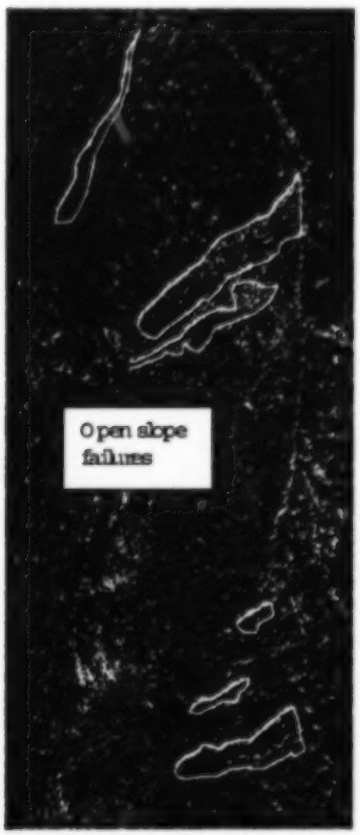

Figure 12c. Open slope failure from IKONOS image.

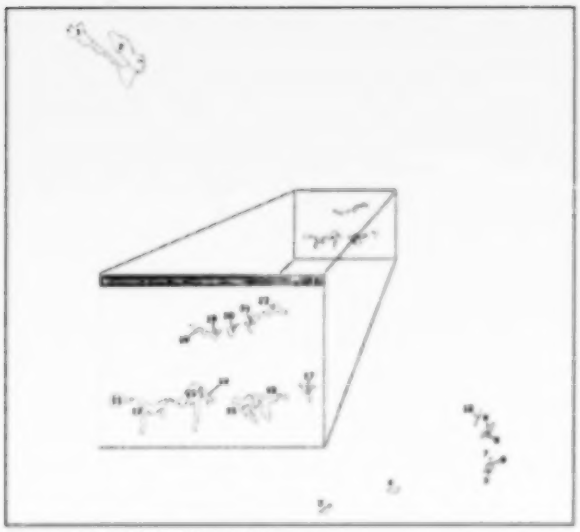

Figure 13. Digitized landslide areas.

Table 5. Area of landslides calculated from IKONOS imagery.

Slides			
ID	Area (ha)	ID	Area (ha)
1	8.77	12	0.54
2	7.47	13	0.69
3	0.49	14	0.13
4	0.55	15	0.37
5	0.34	16	0.48
6	0.05	17	0.14
7	0.05	18	0.10
8	0.24	19	0.10
9	0.60	20	0.09
10	0.20	21	0.13
11	0.28	22	0.18

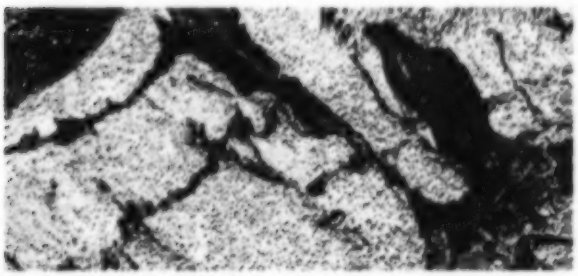

Figure 14. Landslide viewed as IKONOS PCA colour composite.

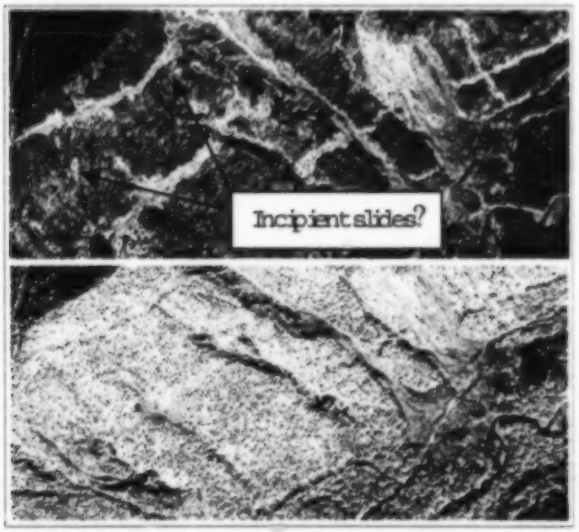

Figure 15. NIR (top) and RGB comparison with Figure 14.

zones. However, areas of purple depict areas that have either thin vegetative cover or are actively raveling and exposing freshly disturbed soil. The spots within the harvested block below the road appear to highlight actively eroding areas or exposed sites that may enlarge. A subset of these sites could potentially denote areas of marginal stability or incipient failure zones. This type of information may be useful for helping to prioritize watershed restoration activities or to highlight problems of road related drainage or maintenance (e.g., incorrect/problematic drainage sources/sites) and to identify sites that require more detailed on-ground investigation. It could also be useful for silviculture purposes to identify areas that require replanting or revegetation.

The NIR composite image also produces similar results and shows areas of thin vegetation cover which may indicate areas prone to erosion or mass wasting. In Figure 15, these areas are shown as light gray or bluish tones in the forested area. These areas are not as easily identifiable in the natural colour composite image. The NIR composite image may be of use for planning future interventions to try to prevent or mitigate the destabilization of these zones. In the NIR colour composite, the landslides and roads both appear in bluish hues.

In the VR block, the particular combination of PC images did not provide any additional visual details compared with the near-infrared image for the area. It is possible, though, that changing the combination of PC images for the colour composite could show additional differentiation. Changing the PC colour combination may also be used to try to enhance differences in forest cover type and/or forest vigor.

3.1.3 LANDSLIDE RECOVERY

The multispectral sensor provides the capability of viewing spectral information in the visible and near-infrared portions of the

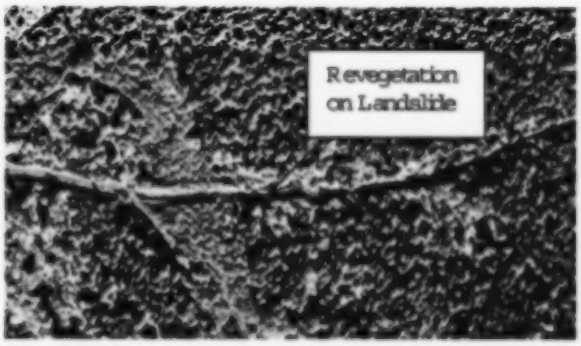

Figure 16. Revegetation example from natural colour IKONOS colour composite image.

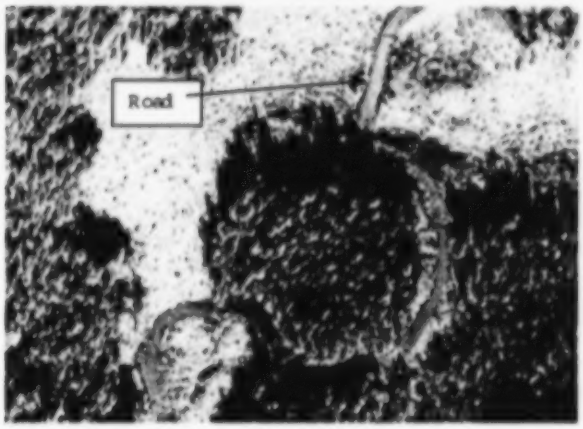

Figure 17. Example of road in IKONOS imagery.

electromagnetic spectrum. Therefore, differences in reflectance can be used to map areas of different vegetation. In Figure 16, older landslides and landslide deposition zones, which have been revegetated, can be differentiated on the optical imagery. This capability could be used for monitoring purposes and could be extended to in-block applications such as assessment of achievement of green-up and free growing requirements.

3.2 ROAD INFRASTRUCTURE

Roads are easily identifiable on the IKONOS imagery (e.g. Figures 16, 17). Total road density by road type (active, deactivated, overgrown) can be calculated. In addition, the total number of road-related point sediment sources can be calculated, and it may in some instances be possible to identify the length of road with high potential for mass wasting, or roads that warrant on-ground assessment. Information relating to the sediment production classification for roads may also be determined. The number of stream crossings is also discernable from the imagery.

Areas of ravel from road fills or areas of road sliver fills can also be delineated (Figure 18). Differentiation between the deactivated road width and the areas of fill or ravel can only be estimated unless there is a noticeable difference in material.

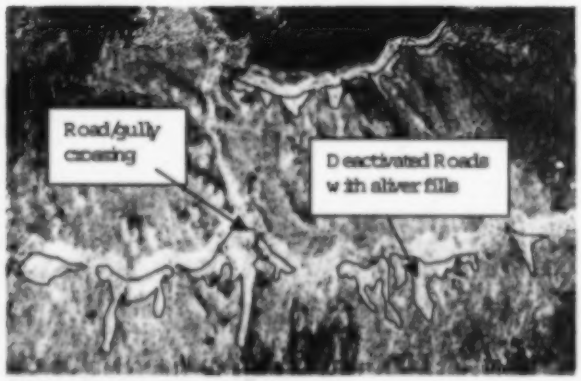

Figure 18. Examples of road ravel.

Figure 18 also shows fully recontoured, permanently deactivated roads. These appear much wider than active roads and merge into the hillslope geometry. These roads would have been grass seeded following deactivation, and subsequently planted with conifers. The vigor of the revegetation compared with the surrounding replanted area could be monitored over time using the NIR imagery.

By utilizing the high spatial resolution imagery, an inventory of all roads, borrow pits, pull-outs and other infrastructure-related features can be determined. This calculation can then provide the total area actually consumed by roads and other man-made non-productive landbase, which forms a direct input to Timber Supply Reviews (TSRs).

3.3 WATERSHED RESTORATION MONITORING

There is a significant and valuable legacy of watershed restoration program overview plans and integrated watershed restoration plans available as a result of Forest Renewal BC funding. However, some of these may have been completed a number of years ago or only partially implemented, and require re-validation of the watershed conditions. The extent and success of rehabilitation efforts and opportunities for rehabilitation may be determined from the IKONOS imagery. This type of imagery could also contribute to access planning, watershed and site level restoration objective planning.

As shown in previous examples, fully recontoured roads and landings are easily discernable on IKONOS imagery. In addition, individual drainage control structures can also be identified on IKONOS imagery. Figure 19 shows individual cross-ditches which have been installed in the Emy Lake area.

Further investigation is required to develop a methodology for monitoring revegetation growth on deactivated road infrastructure.

3.4 COMPLIANCE & ENFORCEMENT APPLICATIONS

Potential IKONOS applications related to Compliance and Enforcement (C&E) functions include the identification of canopy gaps in standing timber (Figure 20), unauthorized harvesting, trespass, road layout, and silviculture prescription monitoring. The technology could have significant application in remote ar-

Figure 19. Cross ditches on deactivated road.

Figure 20. Canopy gap.

eas where tree theft may be a problem. IKONOS imagery could be used for "before" or "after" pictures, or both, to depict conditions that legal teams can easily understand and use when prosecuting C&E cases. As stereo capability becomes available, it may even have the potential to pinpoint individual tree gaps.

High spatial resolution imagery could potentially be used for harvesting and silviculture activity monitoring, and reconnaissance and assessment of compliance with approved operational plans. Images could assist field staff prioritize areas that require more detailed on-ground inspection.

3.5 VEGETATION TYPE

The IKONOS multispectral sensor provides the capability of viewing spectral information in the visible and near-infrared portions of the electromagnetic spectrum, and as vegetation reflects more infrared light than green light, the resultant spectral curves can be used to discriminate between various land cover types. Different types of vegetation have variances in tone and colour because they have different light reflectance properties. Figure 21 shows the differences between the RGB, NIR and PCA images for alder growth on an inactive riparian road.

The use of IKONOS imagery in its various forms warrants further investigation into its ability to help determine vegetation types and possibly the vigor of vegetation (forest health). While IKONOS may not prove reliable enough to always determine vegetation types by itself, it may do so in conjunction with other information such as ecosystem classification, elevation, aspect, and disturbance histories. It may also be of use for silviculturalists in determining where inter-tree species competition may be a problem in achieving free-growing status.

3.6 WINDTHROW

Individual standing trees and leave strips are readily identifiable on the IKONOS imagery (Figure 22). Therefore from a change detection perspective this high resolution imagery should prove useful. No extensive areas of windthrow were discernible within the present coverage area. However, following events such as severe coastal winter storms, IKONOS imagery could assist in de-

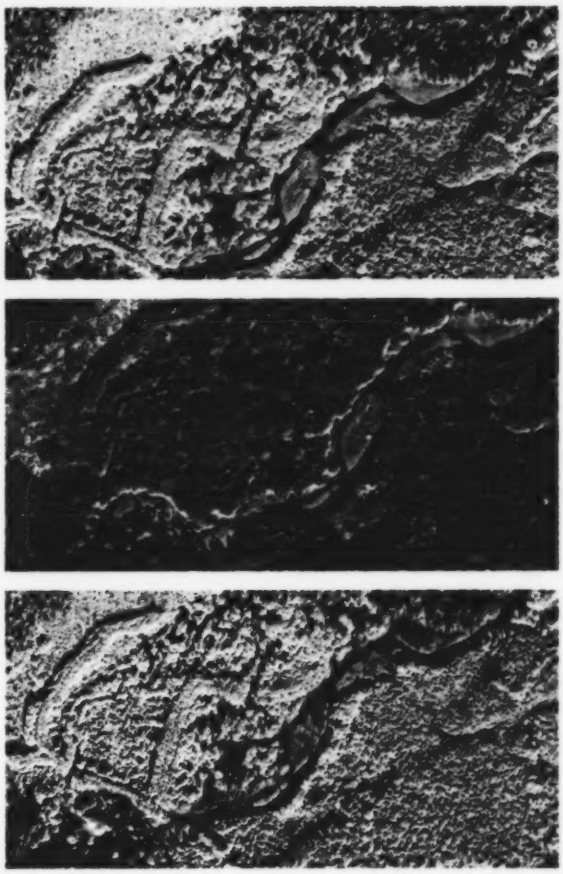

Figure 21. Examples of alder growth on an inactive riparian road (top: RGB; middle: NIR; bottom: PCA).

tecting and assessing the extent and nature of windthrow events, and help in the planning of salvage and clean-up operations.

3.7 COASTAL WATERSHED ASSESSMENT PROCEDURE (CWAP)

The purpose of the CWAP is to provide watershed-level recommendations for forest development plans, based on an assessment of the potential for cumulative hydrological effects from past and proposed forest harvesting and road building (Ministry of Forests, 1999).

The IKONOS imagery can be used to provide detailed information for the following assessment components of the WAP:

- Sediment source survey;
- Riparian assessment;
- Reconnaissance Channel Assessment Procedure (ReCAP).

The typical outputs from these assessments are listed in the CWAP guidebook (Ministry of Forests, 1999). Stand height and canopy density are apparent in some areas by comparing the RGB, NIR and PC images. The percentage of a watershed that is harvested may be calculated. There is significant potential for further development of image analysis techniques to enable a calculation of the Equivalent Clearcut Areas (ECAs) for watersheds by using input from the IKONOS imagery.

3.8 CHANNEL MORPHOLOGY

Analysis of the IKONOS imagery provides some information on alluvial stream reaches, and enables identification of major tributary channels within a watershed, locations of major sediment inputs, obvious channel disturbances, and the location of intact or disturbed riparian areas.

Images could be used for long-term channel monitoring (e.g., Figure 23). Visible in this image are two large woody debris pieces within the channel. Taking measurements from the image indicate that the lengths of these two logs are 25.1 m and 31.8 m. The shorter log is approximately 1.2 m in diameter, the longer log approximately 1.4 m in diameter. However, this channel width is large; on narrower channels, shadows from riparian leave strips occasionally obscure the channel.

3.9 COARSE WOODY DEBRIS

The IKONOS imagery could be used as a component of a multiphased approach to determining the extent of coarse woody debris (CWD) on cutblocks (Figure 24). The number of large pieces of a specific length can be measured from the imagery. In addition to the large piece-size lengths, estimates of diameter can be measured and therefore some estimate of the volume of CWD per hectare can be made. This work could then be followed by on-ground assessment for classification purposes at specific sites. In addition, as seen in Figure 25, the presence of burn piles of CWD, or evidence of post-burn "footprints" of piles, can be seen adjacent to some roads in the image. If burn piles were detected pre-burn, then estimating some of the pile heights could allow the volume of CWD to be calculated.

On a related matter, the IKONOS imagery could be useful for

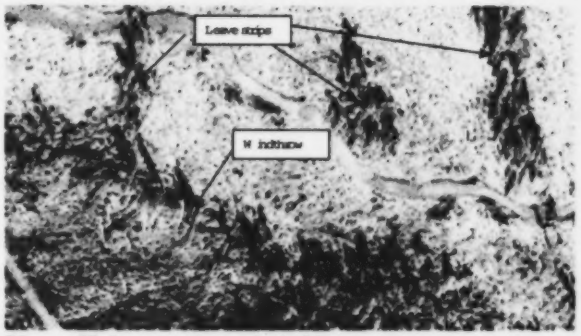

Figure 22. Leave strips and windthrow.

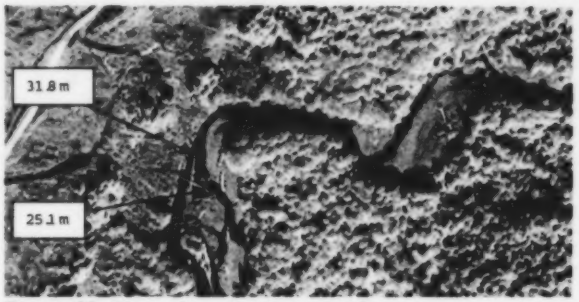

Figure 23. Channel monitoring example.

Figure 24. Presence of CWD can be enhanced by manipulation of the transform histogram to brighten the CWD and darken the surrounding vegetation.

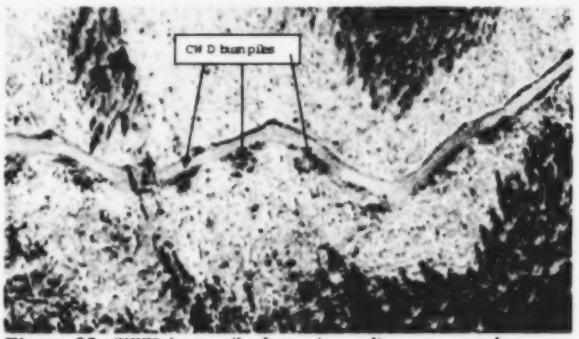

Figure 25. CWD burn pile footprints adjacent to road.

preliminary waste assessments and helping to determine which harvested areas need follow-up ground surveys to determine what is waste as per cutting permit specifications versus what is legitimate CWD.

3.10 TENURE MAPPING

International Forest Products Limited (Interfor) is utilizing variable retention harvesting methods on a new harvest block in TFL 54 within the Escalante watershed. This new block, designated Block Z10G, has an area of 15.9 hectares according to the cutting permit application. VR blocks present new issues to forest resource managers in relation to area calculations. Therefore, to test for area variations, the block boundary was digitized from the NIR image as were the standing tree reserves within the block (Figure 26 a, b, c). The area encompassed by the digitized boundary is equal to 11.39 ha while the reserves total 2.61 ha.

A review of the cutting permit application map for this block shows that its outer boundary, at the point immediately before the road branches, is somewhat larger than that digitized on the above image, and this accounts for the difference in calculated areas. In addition, the digitizing was done without the benefit of stereo imagery and therefore the linework corresponds to a point at the top of tree height. If stereo imagery was available, it might be possible to more accurately digitize the line closer to the base of the trees.

Areas calculated from the digitized IKONOS image:

VR BLOCK	Area (ha)
Block Boundary	11.39
Reserve Areas	2.61
VR Block	**8.78**

These area variations are behind numerous resource management and administrative issues that the Ministry of Forests and industry need to more accurately and systematically address. For any given road or cutblock, area and location estimates or measurements will occur at a number of stages in the development process. Initially, the road or cutblock will appear in a Forest Development Plan (FDP) as a proposed area of development. Area and location are typically estimated at this point, using maps, aerial photography, local knowledge, and whatever useful source information is at hand. Once the road or cutblock is approved in the FDP, the area typically moves forward to the cruise, layout and silviculture prescription / road layout and design stage. Area and location then moves from estimation to measurement, typically utilizing large scale photography (for which IKONOS imagery could substitute) and ground-based methods (e.g., traverse and/or GPS). After the cutblock is harvested and/or the road built, the development is typically located and measured again, via one or more surveys and, usually, ground-based methods. In summary, any given road or cutblock can possess the following areas / locations throughout its development history:

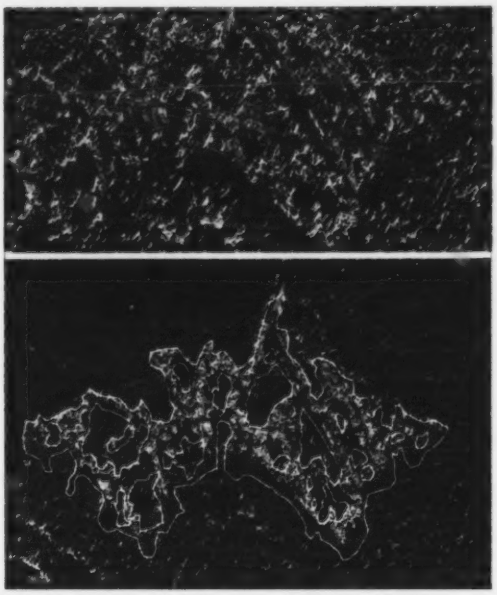

Figure 26 a, b. Variable retention block Z10G.

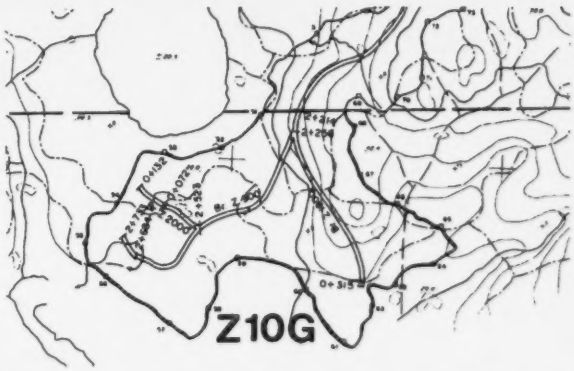

Figure 26c. Block Z10G cutting permit application boundary.

Development Stage	Mode of Estimation/Measurement	Relative Accuracy
FDP (proposed)	Maps & Aerial Photos	Low
FDP (approved)	Ground, large-scale photos	Moderate
Cutting Permit (CP)	Traverse / GPS (pre-harvest)	Moderate-High
Silviculture Prescription (SP)	Traverse / GPS /photos	Moderate-High
Surveys (post-harvest)	Traverse / GPS (as built)	High
Inventory Update	All the above & satellite imagery	Variable

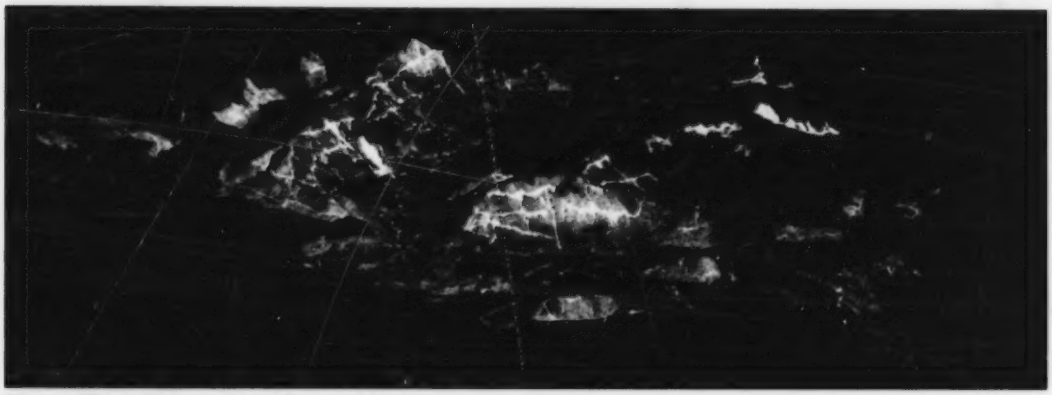

Figure 27a. DEM overview of area of interest.

Figure 27b. DEM of north fork of the Escalante River. Note the relief stacking in the background.

One consideration that may be evident from the above developmental history is that there at least six separate opportunities to derive an area and location for any given road or cutblock. With the disparity of tools typically used for these purposes, and the associated variances in their accuracy and precision, it should come as no surprise that areas and locations can and will vary for any given road or cutblock as it proceeds through the developmental cycle. This often leads to a wide array of resource management and administrative problems, e.g.:

- The Exhibit "A" of the cutting or road permit provides the area legally approved for development under a Forest Act tenure, but if subsequent harvesting or road building strays outside the Exhibit "A" boundary, an approved amendment is required or the outside area will legally be in trespass. What if different area measurement methodologies yield different results? They often do.
- The SP provides internal detail for a proposed cutblock, regarding what areas will be harvested, or retained, or are natu-

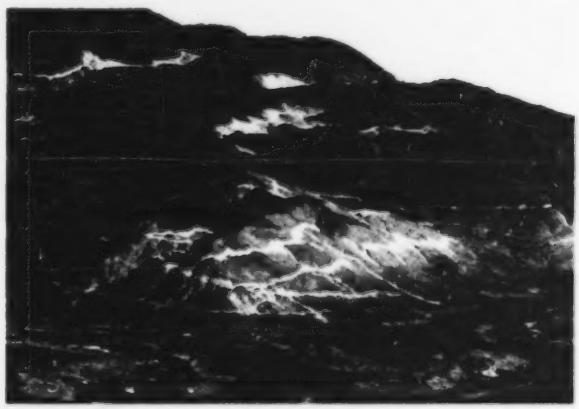

Figure 27c. DEM of the Emy Lake area showing the fully recontoured deactivated roads in the foreground.

ral or man-made non-productive land base. For a typical clearcut block the external boundary of the Exhibit "A" and SP should be the same, but often they are not. The situation becomes more complicated for partial harvest cutblocks such as the above example of variable retention, where internal variations between the Exhibit "A", SP, and what is actually harvested or developed can cause resource management and administrative problems. Different administrative systems employed by the Ministry of Forests and industry may record different areas and locations (the above VR block is a good example), leading to disputes and misunderstanding in the area of fulfillment of legal obligations and maintenance of accurate and consistent databases.

- Areas determined post-harvest or development are generally the most accurate and precise, since the as-built condition reflects reality as opposed to planning. Here IKONOS could provide an excellent tool for "proofing" earlier ground-based methods, and for doing preliminary assessments to see whether there are any significant resource management or administrative issues, as per the above. In the absence of earlier ground-based measurements, IKONOS imagery on its own could potentially provide the area and location accuracy and precision that is required to meet the preset mapping standards. This example also demonstrates that the IKONOS imagery can be used to calculate the net area to be reforested (NAR) for this type of harvesting.

3.11 DIGITAL ELEVATION MODELS

A Digital Elevation Model (DEM) provides a three-dimensional perspective of a landscape by showing a continually varying surface with a draped aerial image that is useful for interpretive purposes. This is particularly important for landscape planning, terrain mapping, and infrastructure engineering projects. A number of DEMs (Figure 27) were generated using the elevation data from the TRIM topographic databases, with the IKONOS imagery draped over the model. Some distortion does occur and the imagery does appear to have a "stacked" relief in the background.

3.12 INVENTORY UPDATE

Traditionally, forest cover or vegetation inventories have been built by first acquiring medium-scale aerial photography (most recently 1:15,000 color), followed by delineation of polygons on stereo pairs and associated attribute estimation by trained forest classifiers. As IKONOS imagery is not stereo, it would not be particularly useful for building a new vegetation inventory. However, for inventory update, IKONOS imagery could have considerable potential. For update purposes, newly harvested openings, roads and natural disturbances (e.g., fire, blowdown, insect infestation) are traditionally captured spatially by either ground-based methods (traverse, GPS) or periodic aerial photography. Orthorectified IKONOS imagery appears to be as accurate as these traditional methods, if not more so. The biggest issues will likely be access to the right imagery at the right time, and cost. However, there is potential to add one more tool to the inventory update toolbox. For example, other forms of remote sensing may be used to initially detect new disturbances (e.g., Landsat), followed by more accurate and detailed spatial delineation of features by IKONOS imagery over specific areas of activity, ground-based measurements, or whatever tool is most effective and cost-efficient under the particular set of circumstances.

It should also be noted that remote sensing imagery such as IKONOS can provide ancillary benefits such as information about adjacent areas, whereas ground-based methods generally only provide information about the specific areas of interest. IKONOS imagery could also be a potentially excellent tool for updating orthophotography images, via a "cut and paste" methodology. Having a visual backdrop to conventional polygon linework on maps (e.g., see the actual tree cover behind the proposed wildlife tree patch) has made the use of ortho imagery extremely popular for land use planning purposes, particularly where referral to the public and non-forest industry stakeholders is involved. Rather than having to regularly reacquire expensive orthophotography, IKONOS could be used to keep the orthophotos "current" for a considerably longer period of time, via this "cut and paste" of IKONOS images methodology.

3.13 LAND USE PLANNING

Due to its high spatial resolution, the IKONOS imagery could form an important tool for strategic planning where planners are focused on ecosystem based management principles. Determination of features and attributes useful for forest resources management (e.g, identification of seral stage distribution, general vegetation types, recreation features, critical wildlife habitats) are possible. There is also a role for this imagery in planning for the establishment of protected areas, Old Growth Management Areas, Wildlife Habitat Areas, and other strategic land use planning designations or zonations. For the forest industry, this technology can be useful for assisting with economic profitability estimates of specific watersheds and other potential operating areas.

3.14 OPERATIONAL PLANNING

The utility of IKONOS imagery for operational planning purposes requires further investigation. However, some of the possibilities are immediately apparent. Similar to large-scale aerial photography (e.g., 1:10,000 or larger) there appears to be sufficient image information to enable gathering of, or input into, operational planning requirements such as reconnaissance-level terrain stability mapping, tentative stream and riparian classification, preliminary road and cutblock layout, ecosystem classification, green-up and adjacency, wildlife tree patch retention, and possible forest health issues. Much of this imagery data will ultimately need to be verified or amended by field inspection, but such is the case for other forms of high-resolution remote sensing, including conventional large-scale aerial photography.

3.15 FUTURE USES

There are other potential applications for the high spatial resolution imagery. Among just some of the uses are post-fire damage assessment, forest health and infestation monitoring, and change detection. There are plans for the launch of additional satellites with stereo imagery capability and hyperspectral capabilities which will provide additional opportunities for the use of satellite imagery in forest resource management.

4.0 COST COMPARISON

Different levels of IKONOS image accuracy are available at varying prices. The more precision required in an image, the higher the cost.

The IKONOS pricing for this pilot project was US$12/Km^2 ($0.12 per hectare) for panchromatic and the same for the 4m multispectral imagery, at the single-agency price scale. However, both the panchromatic and MSS together were available at a cost of US$18/km^2. The minimum order size at the time of acquisition was US$1000, which equated to a coverage of 55 km^2. A multi-agency cost estimate (single-agency cost x 1.4) for an area equivalent to a 1:20,000 map sheet is approximately $4,389 (G.Weir, pers. Comm). This equates to approximately $0.27/ hectare prior to any image processing.

One cannot assume that both image formats will be perfectly co-registered in areas of significant terrain relief, hence some additional costs may be incurred in image processing to correct the imagery. The more mountainous the terrain, the more fine tuning of the co-registering and geocoding will be required.

Costs for processing the data would include time for a remote sensing analyst. For the IKONOS orthorectified product the pricing was US$66/km^2, and the precision product was priced from US$66 to $76 per km^2. Up-to-date pricing for Canadian imagery is available from the following web sites: Space Imaging at http://www.spaceimaging.com; RSI at http://www.rsi.ca/storefront/high_res_usd.htm#top, and Pacific Geomatics Ltd. at http://www.orthosat.com. There are also licensing issues (single-agency versus multi-agency), data sharing, and multiple use issues that would need to be addressed for more widespread use of this data. Cost estimates will vary depending on specific project factors such as time, size of data order, and amount of data to be processed.

There was a standing-order arrangement in place through the Government of BC for the purchase of RADARSAT-1 images at the time of this pilot project, and the price was $650 per scene.

As a comparison, another option available to forest managers is that orthophotographs are available for some areas; for example, a forest licensee has orthophotographs available for the east coast of Vancouver Island at approximately $400 per mapsheet. A BCGS 1:20,000 mapsheet covers about 16,000 hectares, thus the cost is about $0.025 per hectare. Unfortunately, the rest of the district is not covered the same way. In the Queen Charlotte Islands, a set of black-and-white ortho-photos with a 1m resolution was acquired in the late 1990s at a cost of approximately $0.069 per hectare. However, costs are also dependant on the coverage area being surveyed.

GPS typically costs $100 to $200 per linear kilometer. A typical 40 hectare opening could have an external boundary of about 3 km, thus costing about $300 to $600 to accurately locate and measure with GPS, or about $7.50 to $15.00 per hectare. If GPS data collection is not subcontracted, then the cost factors for in-house collection would include purchase of the GPS unit(s), post-processing software, and a GPS specialist to do the processing.

From a cost-benefit analysis perspective the costs of mobilizing a crew by helicopter, fixed wing or boat to a remote site can be substantial. So too can the cost of acquiring aerial photographs or traditional ortho-photos of an area where the resulting product does not contain the range of multispectral information of satellite imagery (e.g., NIR). IKONOS imagery in addition has 11 bits of information per channel, while photogrammetric software works with eight bits of information per channel. Satellite digital imagery also provides the image analyst with more flexibility in enhancing the differences within an image (e.g., through the use of Principal Component Analysis or simple contrast stretching), and the ability to merge images from multiple dates (e.g., for change detection) or multiple sensors. Delivery times for satellite imagery may also be faster than those for aerial photographs, but both are weather dependent.

The software used for this project included PCI®, which is available in modules at a cost of approximately $25,000 to $30,000. ERMapper® is available at a cost of approximately $5000, but there is a free ERMapper® viewer available for download from the company's website at http://www.ERMapper.com. Among the viewer's capabilities are tools to enable the processed images to be viewed and individual features to be measured.

5.0 CONCLUSIONS

Remote sensing technology offers a number of options for the ability to view areas for the purposes of sustainable forest management. The challenge for forest resource managers is how to effectively use these tools for maximum benefit at minimum cost to meet forest management application needs. This pilot-project tested the benefits of using IKONOS data for such applications, and also tested the utility of RADARSAT-1 data fusion for use as a monitoring tool during the winter or cloud-covered periods.

While RADARSAT-1 imagery has the advantage of being weather-independent, the utility for routine forest resource management at an operational level requires expertise that is available only to a limited number of specialists. The use of stereo pairs could be of more use in operational forestry and terrain analysis applications than is shown in this pilot project. RADARSAT-1 stereo pairs are available with a minimum of 60% overlap in coverage area. In this study, the RADARSAT-1 imagery was not able to provide us with more information than what we could derive from the IKONOS imagery. It was hoped that landslides, the VR block, and geological structures (e.g., faults) could be identified in the RADARSAT-1 imagery. But it was very difficult to identify these features without aid of the IKONOS imagery. Varying the incidence angle for the RADARSAT images also did not appear to provide us with additional ground details.

Remote sensing using IKONOS high spatial resolution optical data is an important and cost-effective tool in assessing and managing forest resources. Most forest management activities involve the production of detailed maps, which usually require significant amounts of data compiled from on-ground observations. Multispectral satellite imagery is becoming more impor-

tant in the mapping process and has particular benefits in remote and inaccessible areas. IKONOS satellite imagery provides excellent input for mapping, inventorying, monitoring and surveying forest resources.

Some of the advantages of the IKONOS satellite imagery include the capability of providing greater information content than traditional aerial photographs, and information is automatically captured in digital format versus conversion to format for photography. Acquiring high spatial resolution imagery provides panchromatic, natural colour, and NIR spectral information in digital format at the same time. This makes it unique and potentially very useful compared with orthophotography. It allows digital processing such as orthorectification, enhancement, classification, and direct transfer to GIS databases. IKONOS products are available as 11-bit black-and-white and 11-bit colour providing 2,048 shades of gray/colour compared with the traditional 8-bit data used in orthophotographs, which provides 256 shades. The 11-bit data is useful for viewing details in shadowed areas or areas that are very bright. In addition, there is no problem with colour matching across photos, or worrying about the state of the different chemicals for the development of the film, as is the case with aerial photography. Digital images can be used to create an archive of co-registered data, which can be used to monitor changes over time.

It should also be noted that remote sensing imagery such as IKONOS could provide ancillary benefits such as information about adjacent areas, whereas ground-based methods generally only provide information about the specific areas of interest. IKONOS imagery could also be a potentially excellent tool for updating orthophotography images, via a "cut and paste" methodology. Having a visual backdrop to conventional polygon linework on maps (e.g., see the actual tree cover behind the proposed wildlife tree patch) has made the use of ortho-imagery extremely popular for land use planning purposes, particularly where referral to the public and non-forest industry stakeholders is involved. Rather than having to regularly reacquire expensive orthophotography, IKONOS could be used to keep the orthophotos "current" for a considerably longer period of time.

Based on these preliminary assessments, this work demonstrates the capabilities of high spatial resolution IKONOS satellite imagery to discriminate and map forest resource features. The high spatial resolution IKONOS imagery is an important tool in the assessment, characterization and documentation of the main forest resource features in a watershed, and provides a new and valuable source of detailed information for environmental monitoring and development planning.

Further work is required to demonstrate the application of this type of imagery to vegetation inventories. However, this type of imagery should form an integral part of the toolkit available to forest resource managers. The use of IKONOS satellite imagery is a cost-effective method for detecting changed conditions over large areas, which should reduce management costs.

From the current trend in types of satellites being designed and launched, it appears that satellites with more spectral channels (e.g., hyperspectral sensors with 256 channels) and greater spatial resolution (e.g., sub-metre) will become available over the next few years. The ASTER sensor from NASA is one hyperspectral sensor that is currently providing images for research purposes. The addition of stereo capability will greatly enhance the application of this type of data to forest resource management. One such satellite with stereo capability, Quickbird owned by Earthwatch, was launched in November 2000. However, it failed to reach orbit after launch. A duplicate satellite is scheduled for launch later in 2001.

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APPENDIX A: GLOSSARY OF TERMS

Active Sensor: a type of sensor which provides its own energy source for illumination. The sensor emits radiation which is directed toward the target to be investigated. The radiation reflected from that target is detected and measured by the sensor.

Automated Gain Control: an image processing technique for auto-correcting for water/land differences in RADAR backscatter.

Backscatter: The antenna receives a portion of the transmitted energy reflected (or backscattered) from various objects within the illuminated beam.

Brightness: Image brightness is influenced by terrain properties (local incidence angles) and parameters of the RADAR system. Brightness is directly proportional to the amount of radiation reflected back to the RADAR system. Rough surfaces and small local incidence angles appear bright in SAR imagery because more microwave energy is reflected to the satellite. Smooth surfaces and larger local incidence angles appear dark because microwave energy is reflected away from the satellite.

Correlation Eigenvector Matrix: a matrix containing factor loadings produced through Principal Component Analysis. This matrix is used to rotate the axes of the input satellite imagery to form new PCA images.

Digital Elevation Model (DEM) provides a digital representation of continuous relief variation over space.

Foreshortening: an effect which commonly occurs when viewing mountainous slopes orthogonal to the RADAR beam. This results in the slope image being compressed in length and is represented by a bright RADAR response. The mountain slopes on the back side are darker and longer. This gives the appearance that the mountains are leaning over.

Geometric rectification: a process by which the geometry of the image area is made planimetric.

Ground Control Point (GCP): a point on the earth's surface where both the image coordinates and map coordinates can be rectified.

Incidence angle: the primary parameter for slant range to ground range conversion.

Layover: the extreme form of foreshortening where the top of the mountain is imaged before its base. The result is an image with the peak "laid over" its base.

Moisture content increases the dielectric constant, which in turn affects the reflectivity of the surface. A wet rough surface has a brighter appearance than the same surface when dry.

Orthorectification: an image processing technique that removes distortions from the collection geometry and resamples the image to a uniform ground distance and user-specified map datum.

Passive Sensor: This type of sensor can only be used to detect energy when naturally occurring energy (such as sunlight) is available. For all reflected energy, this can only take place during the time when the sun is illuminating the Earth.

Pixel: the smallest digital element which comprises the image data set.

Polarization: the orientation of the electric field.

Principal Component Analysis: a digital image enhancement technique that uses a multivariate analysis method to reduce the number of variables in a data set.

RADAR: acronym for "RAdio Detection And Ranging." This instrument is used to transmit microwave or radio signals, receive backscatter, and measure the intensity and time delay of the return signals.

Resolution: when used in reference to a sensor, refers to the size of the smallest possible feature that can be detected.

Shadow: the area not illuminated by the RADAR beam. Shadow is normally not a factor in RADAR images using steep incidence angles.

Slant range: the line of sight between the RADAR and each reflecting feature on the surface.

Speckle: a type of interference, or noise, which is intrinsic to Synthetic Aperture Radar (SAR) images, and is a significant issue with respect to data analysis. Speckle noise is manifest on an image as a grainy surface which decreases the resolution of the underlying data.

Swath: the width of the area of ground coverage of the satellite.

Synthetic Aperture Radar (SAR): a microwave instrument that sends pulsed signals to Earth and processes the received reflected pulses. SAR uses advanced signal processing techniques to simulate the effect of a long antenna. RADARSAT 's SAR-based technology provides its own microwave illumination and thus operates day or night, regardless of weather conditions.

APPENDIX B: RADARSAT GCP LOCATIONS AND RMS RESIDUAL ERROR REPORTS

F1 Residual Error Report

Residual Units: Image Pixels

GCPs: 8 X RMS
1.71 Y RMS
1.16 OVERALL RMS

Point ID	Residual	Residual X	Residual Y	Photo X	Photo Y	Computed X	Computed Y
G0003	3.7	3.5	1.21	5205.5	5405.5	5209	5406.7
G0001	2.6	-1.51	-2.11	4814.5	5122.5	4813	5120.4
G0004	2.47	2.15	1.23	6107.5	5177.5	6109.6	5178.7
G0002	1.54	-0.92	-1.23	6370.5	5886.5	6369.6	5885.3
G0005	0.84	-0.65	0.54	5178.5	5038.5	5177.9	5039
G0006	0.38	-0.16	0.35	4506.5	6757.5	4506.3	6757.8
G0007	0.1	0.04	0.09	2129.5	2109.5	2129.5	2109.6
G0008	0.08	0.02	-0.07	7141.5	1309.5	7141.5	1309.4

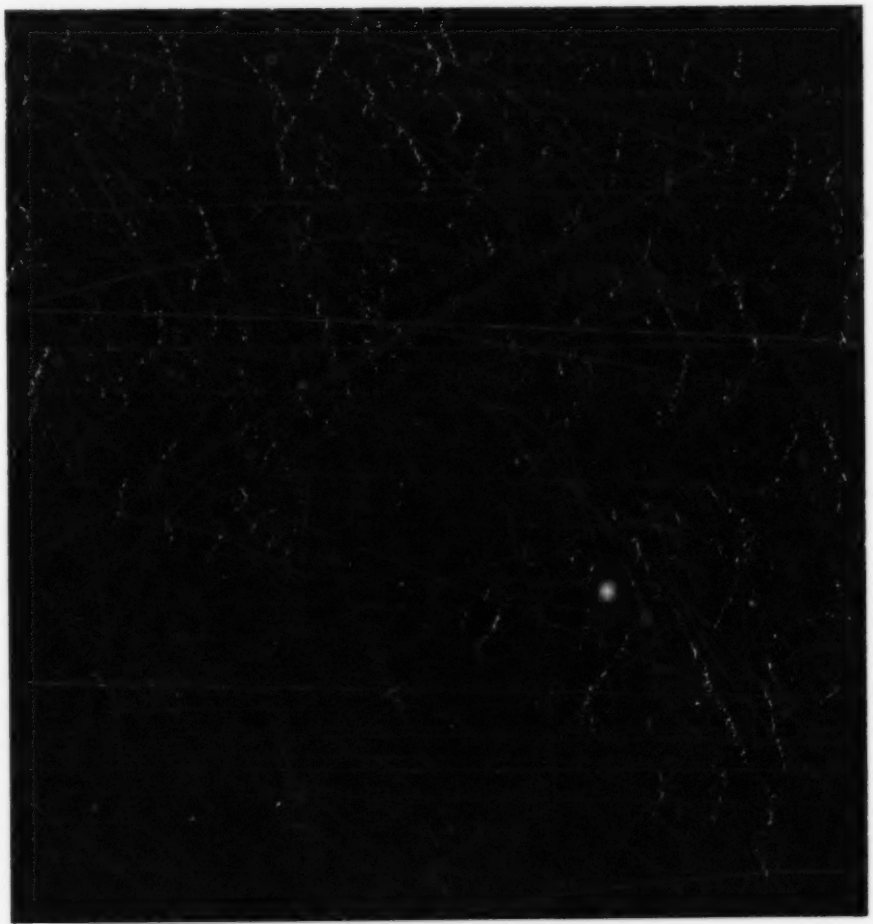
F1 GCP Locations

F2 Residual Error Report (Appendix B continued)

Residual Units: Image Pixels

GCPs: 12 X RMS
2.56 Y RMS
3.03 OVERALL RMS

Point ID	Residual	Residual X	Residual Y	Photo X	Photo Y	Computed X	Computed Y
G0004	7.89	-2.79	7.38	4824.5	6538.5	4821.7	6545.9
G0001	5.15	-1.33	-4.97	4300.3	6790.3	4298.9	6785.3
G0003	5.1	3.82	-3.38	6033.5	6988.5	6037.3	6985.1
G0007	3.87	-3.37	1.9	6089.5	7748.5	6086.1	7750.4
G0009	3.52	-3.34	-1.11	4056.5	6128.5	4053.2	6127.4
G0008	3.48	3.39	0.81	5244.5	4653.5	5247.9	4654.3
G0006	2.83	2.77	0.58	4562.5	8432.5	4565.3	8433.1
G0005	1.78	1.51	0.94	759.5	4837.5	761	4838.4
G0002	1.78	0.68	-1.64	4329.5	6713.5	4330.2	6711.9
G0011	1.68	-1.51	-0.74	518.5	1586.5	517	1585.8
G0012	1.09	1.03	0.35	1874.5	257.5	1875.5	257.9
G0013	0.59	-0.58	-0.12	7549.5	70.5	7548.9	70.4



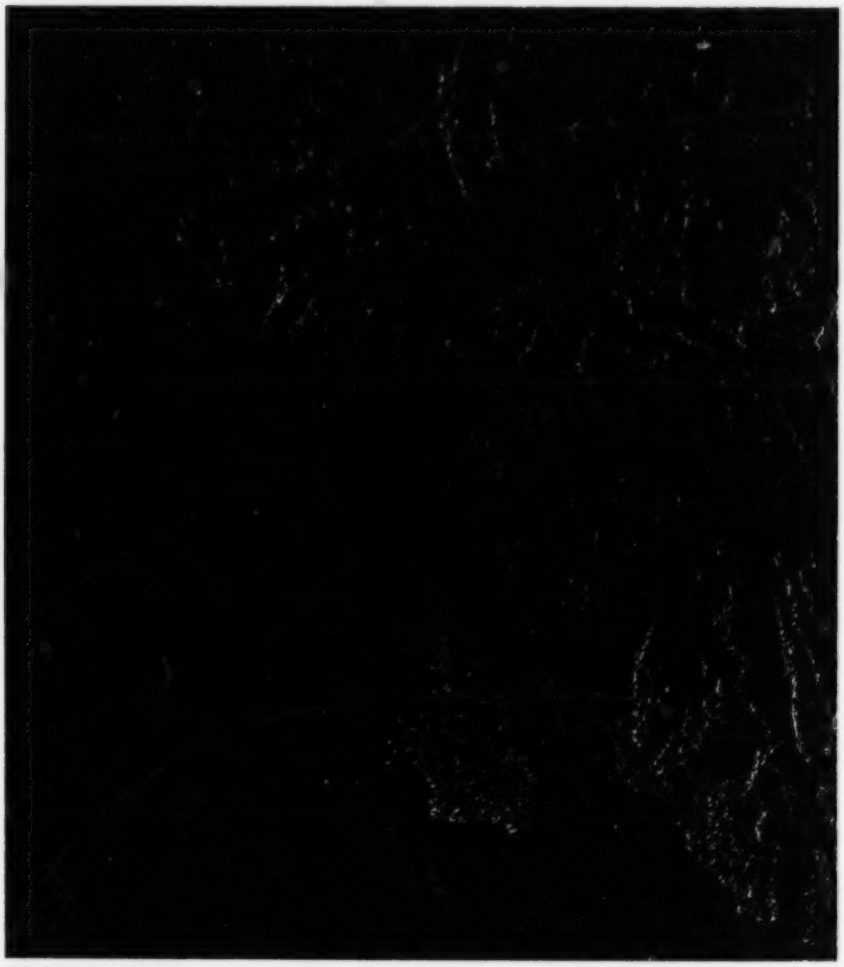
F2 GCP locations

F5 Residual Error Report (Appendix B continued)

Residual Units: Image Pixels

GCPs: 11 X RMS
2.29 Y RMS
2.06 OVERALL RMS

Point ID	Residual	Residual X	Residual Y	Photo X	Photo Y	Computed X	Computed Y
G0004	5.94	-5.43	2.42	6015.5	5470.5	6010.1	5472.9
G0002	4.54	1.59	-4.25	4432.5	4746.5	4434.1	4742.2
G0011	3.64	-0.72	3.57	4409.5	4039.5	4408.8	4043.1
G0009	3.61	3.42	-1.17	6002.5	3000.5	6005.9	2999.3
G0003	3	2.42	-1.77	4831.5	5018.5	4833.9	5016.7
G0012	1.04	0.97	-0.36	7200.5	8600.5	7201.5	8600.1
G0006	1.02	-0.34	0.96	4169.5	6387.5	4169.2	6388.5
G0008	0.99	-0.97	0.19	5693.5	217.5	5692.5	217.7
G0010	0.75	-0.53	0.53	3292.5	3575.5	3292	3576
G0001	0.31	-0.31	0.04	4487.5	4683.5	4487.2	4683.5
G0007	0.17	-0.07	-0.15	1667.5	1802.5	1667.4	1802.3



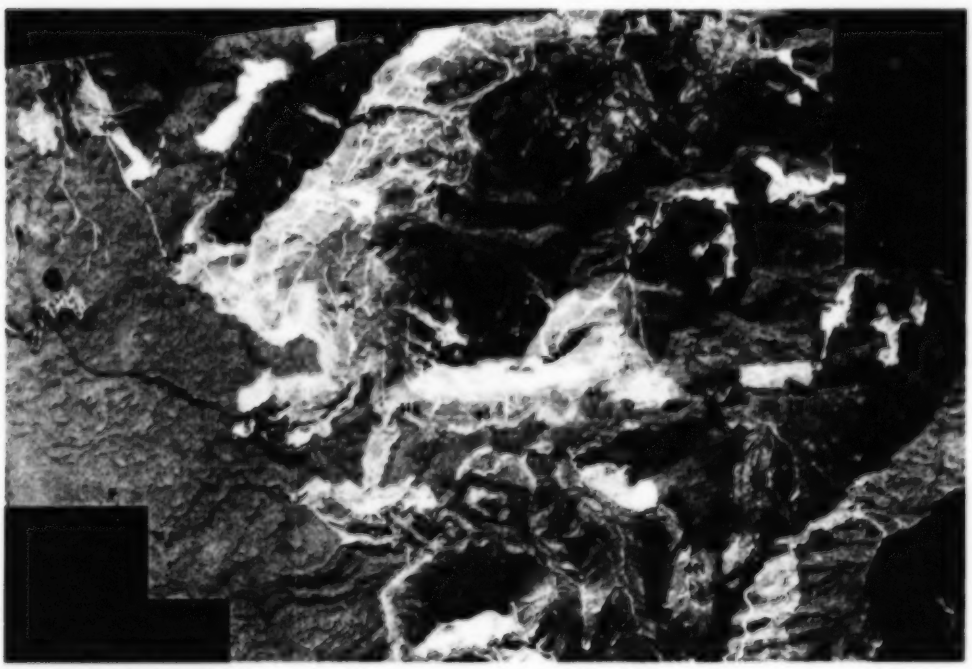
F5 GCP Locations

APPENDIX C: IKONOS GCP LOCATIONS AND RMS RESIDUAL ERROR REPORTS

Residual Units: Image Pixels

GCPs: 17 X RMS
0.49 Y RMS
1.04 OVERALL RMS

Point ID	Residual	Residual X	Residual Y	Photo X	Photo Y	Computed X	Computed Y
10	2.43	0.11	2.42	1127.9	353.6	1128	356
8	1.83	-0.86	-1.62	510.8	771.3	510	769.7
12	1.76	-0.18	-1.75	1974.9	678.1	1974.7	676.4
19	1.41	0.41	-1.35	1915.7	813.6	1916.1	812.2
9	1.12	0.22	-1.09	313.1	370.1	313.3	369
3	1.12	-0.26	1.09	2167.3	1194.3	2167	1195.3
1	0.99	0.6	0.78	1056.9	917.9	1057.5	918.7
5	0.94	0.89	0.31	1465.9	1256.1	1466.8	1256.4
22	0.74	0.58	0.47	1872.6	184.1	1873.2	184.6
20	0.71	0.36	0.61	549.4	746.4	549.7	747
13	0.58	-0.54	-0.23	2241.1	278.9	2240.6	278.6
2	0.56	-0.5	0.25	1808.2	1187.4	1807.7	1187.7
18	0.49	0.47	-0.14	1228.8	1237.6	1229.3	1237.4
17	0.48	-0.46	0.12	1374.1	463.8	1373.6	463.9
7	0.45	-0.4	0.2	96.2	939.7	95.8	939.9
11	0.29	-0.22	-0.19	2117.4	1733.4	2117.2	1733.2
16	0.26	-0.22	0.13	736.6	1261.4	736.4	1261.5



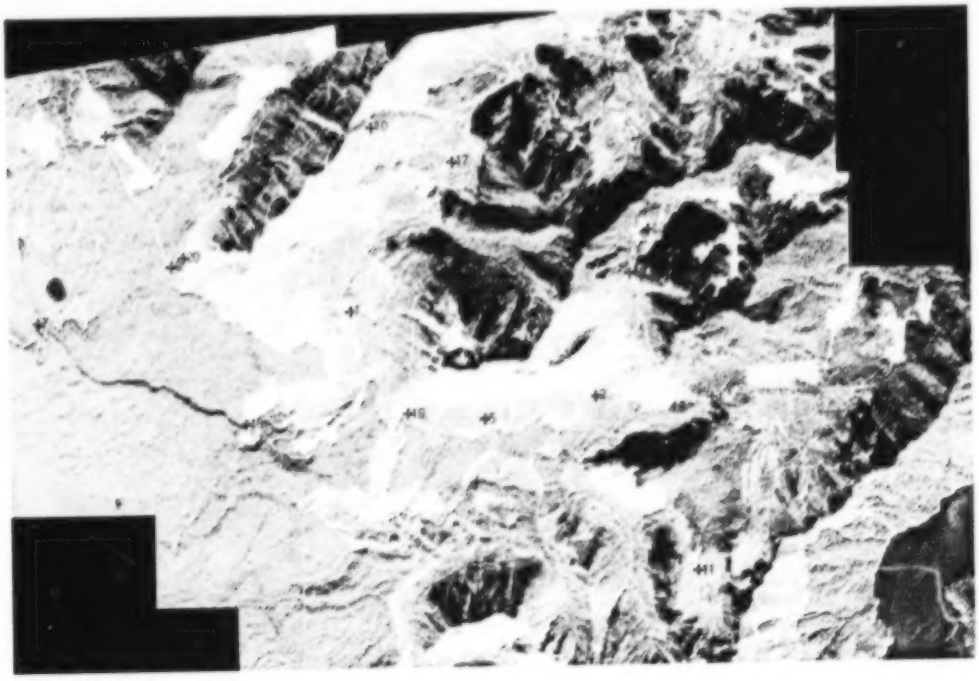
IKONOS GCP Locations

APPENDIX C: IKONOS GCP LOCATIONS AND RMS RESIDUAL ERROR REPORTS

Residual Units: Image Pixels

GCPs: 17 X RMS
0.49 Y RMS
1.04 OVERALL RMS

Point ID	Residual	Residual X	Residual Y	Photo X	Photo Y	Computed X	Computed Y
10	2.43	0.11	2.42	1127.9	353.6	1128	356
8	1.83	-0.86	-1.62	510.8	771.3	510	769.7
12	1.76	-0.18	-1.75	1974.9	678.1	1974.7	676.4
19	1.41	0.41	-1.35	1915.7	813.6	1916.1	812.2
9	1.12	0.22	-1.09	313.1	370.1	313.3	369
3	1.12	-0.26	1.09	2167.3	1194.3	2167	1195.3
1	0.99	0.6	0.78	1056.9	917.9	1057.5	918.7
5	0.94	0.89	0.31	1465.9	1256.1	1466.8	1256.4
22	0.74	0.58	0.47	1872.6	184.1	1873.2	184.6
20	0.71	0.36	0.61	549.4	746.4	549.7	747
13	0.58	-0.54	-0.23	2241.1	278.9	2240.6	278.6
2	0.56	-0.5	0.25	1808.2	1187.4	1807.7	1187.7
18	0.49	0.47	-0.14	1228.8	1237.6	1229.3	1237.4
17	0.48	-0.46	0.12	1374.1	463.8	1373.6	463.9
7	0.45	-0.4	0.2	96.2	939.7	95.8	939.9
11	0.29	-0.22	-0.19	2117.4	1733.4	2117.2	1733.2
16	0.26	-0.22	0.13	736.6	1261.4	736.4	1261.5



IKONOS GCP Locations

APPENDIX D: SCENE STATISTICS FOR IKONOS IMAGERY

Band 1 = Near Infrared
Band 2 = Red
Band 3 = Green
Band 4 = Blue
Band 5 = Panchromatic

	Band1	Band2	Band3	Band4	Band5
Null Cells	36642500	36526100	36458500	36478500	24615300
Non-Null Cells	86323600	86440000	86507600	86487600	98350800
Minimum	-63.1887	-13.7298	-15.8771	-18.3541	1
Maximum	1028.058	491.0062	537.942	424.2976	770
Mean	282.3613	82.89619	134.3102	149.3473	147.7477
Median	256.5124	76.96494	129.0677	145.9112	142.1836
Std. Dev.	155.7354	35.77183	34.52504	20.44728	95.10369
Std. Dev. (n-1)	155.7354	35.77183	34.52504	20.44728	95.10369
Corr. Eigenvalue	3.79772	0.83484	0.31292	0.04498	0.00954

Correlation Matrix	Band1	Band2	Band3	Band4	Band5
Band1	1	0.6197	0.64344	0.4679	0.69247
Band2	0.6197	1	0.98784	0.94003	0.55408
Band3	0.64344	0.98784	1	0.95006	0.5697
Band4	0.4679	0.94003	0.95006	1	0.46869
Band5	0.69247	0.55408	0.5697	0.46869	1
Determinant	0.00043				

Corr. Eigenvectors	PC1	PC2	PC3	PC4	PC5
Band1	0.39367	0.55264	0.70291	0.20109	0.07137
Band2	0.49269	-0.26405	0.04532	-0.5998	0.57072
Band3	0.49793	-0.24158	0.05986	-0.23757	-0.79604
Band4	0.46312	-0.42871	-0.15227	0.73691	0.18841
Band5	0.37399	0.61864	-0.69072	-0.01775	-0.00045